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(54) **PERCUTANEOUS HEART PUMP**

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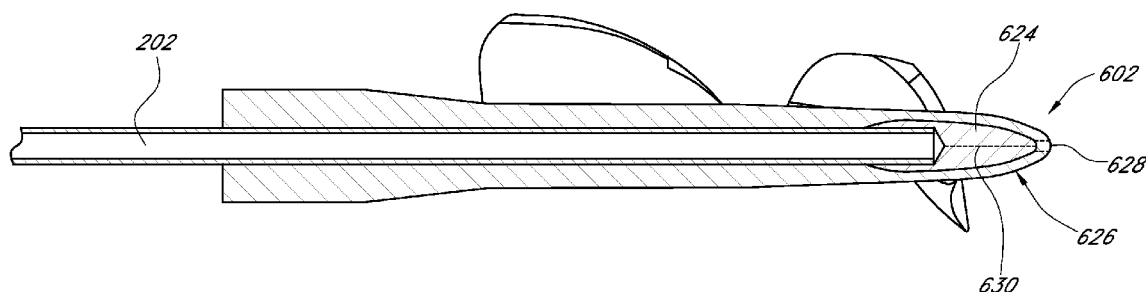
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(57) **ABSTRACT**

Disclosed herein are heart pumps that can include a catheter body and an impeller coupled with a distal end of the catheter body. The impeller can include a tip that is resealable or that includes a resealable member. The heart pump can also include a diffuser disposed between the distal end of the catheter body and the impeller, wherein the diffuser includes a flow directing surface.

**26 Claims, 26 Drawing Sheets**



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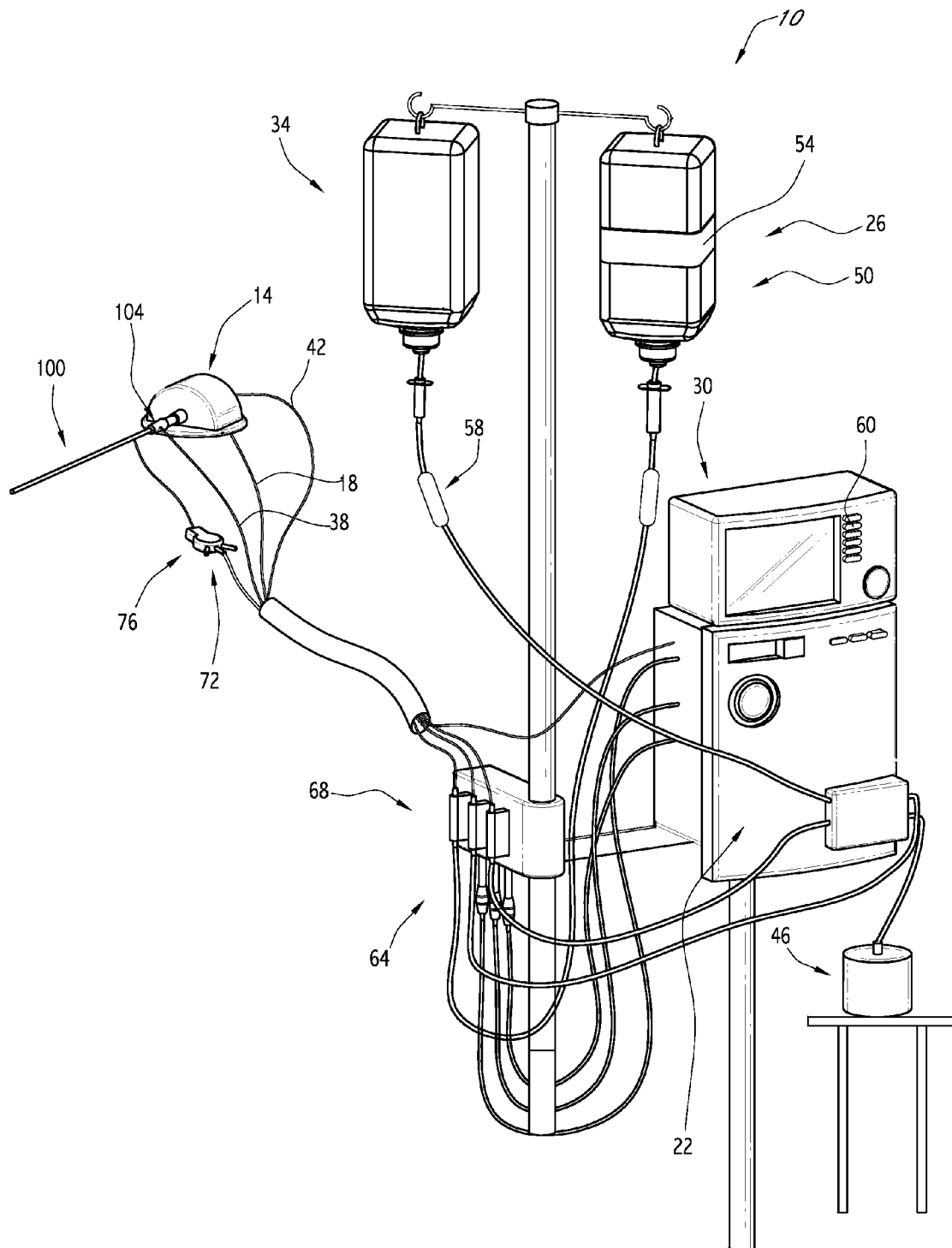
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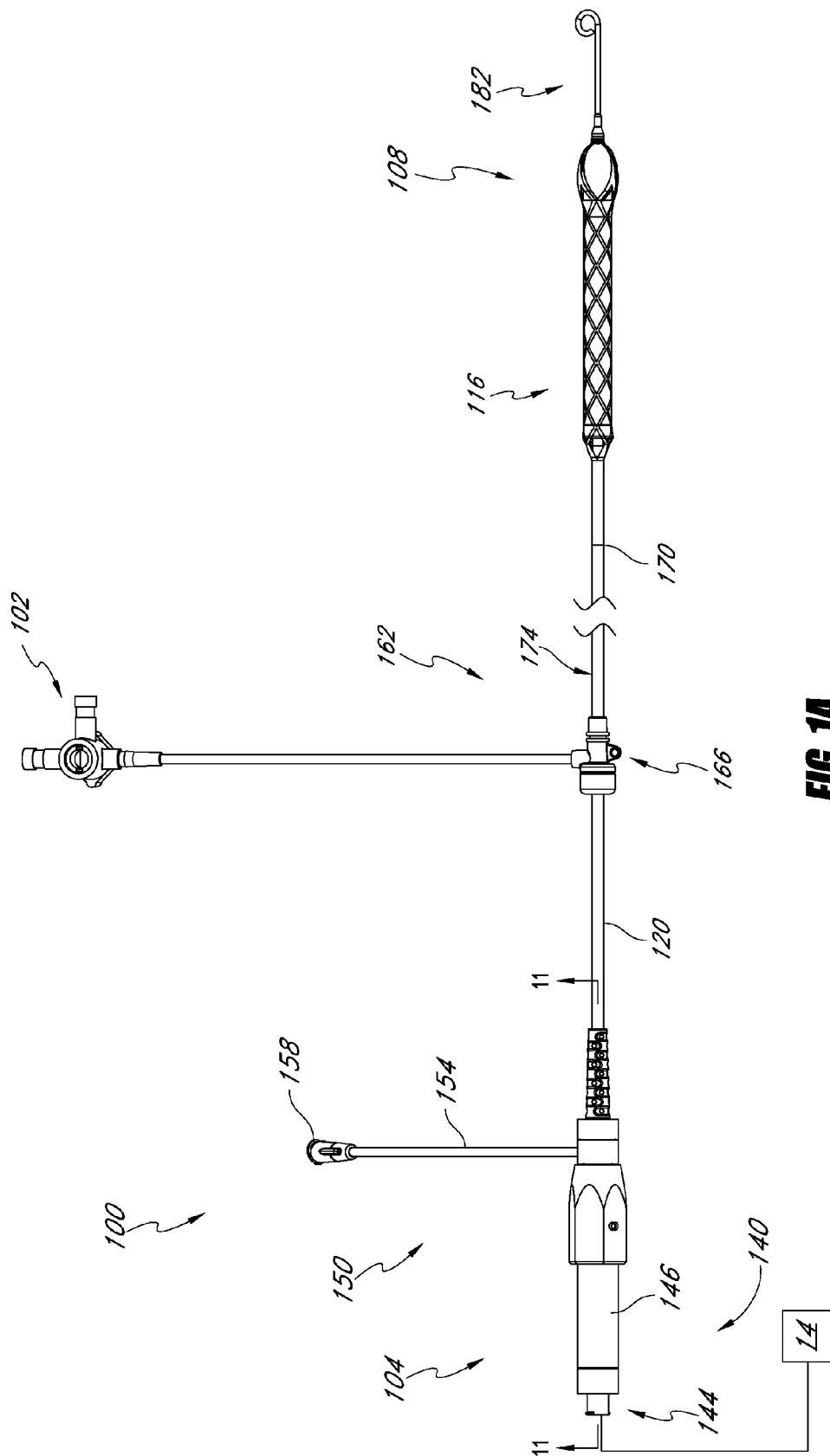
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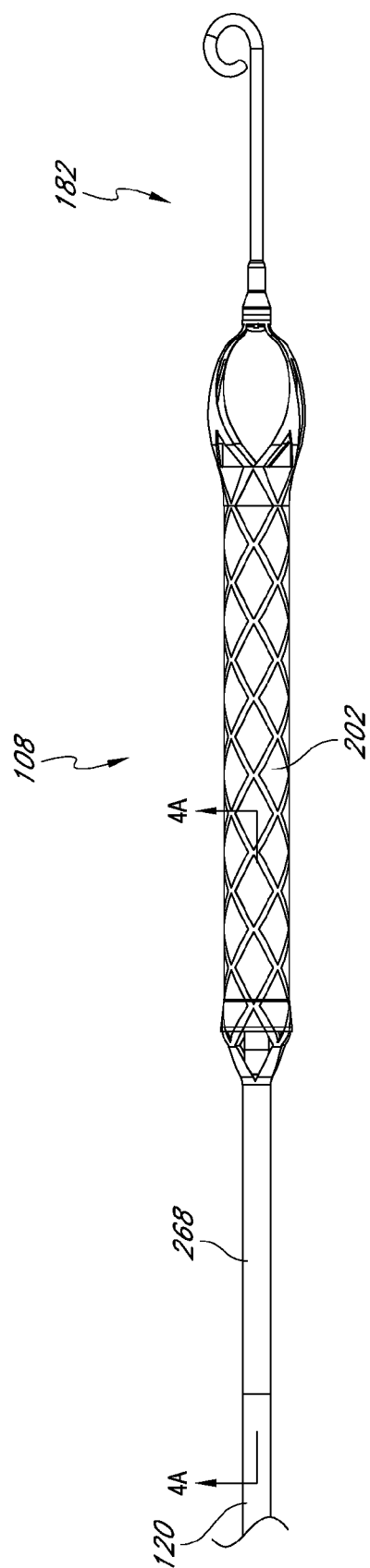
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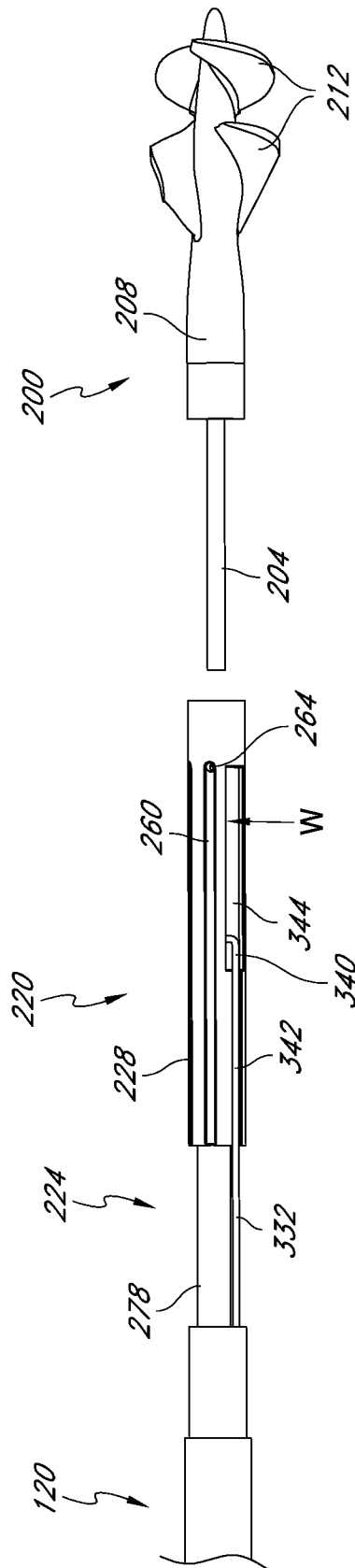
**FIG. 1**



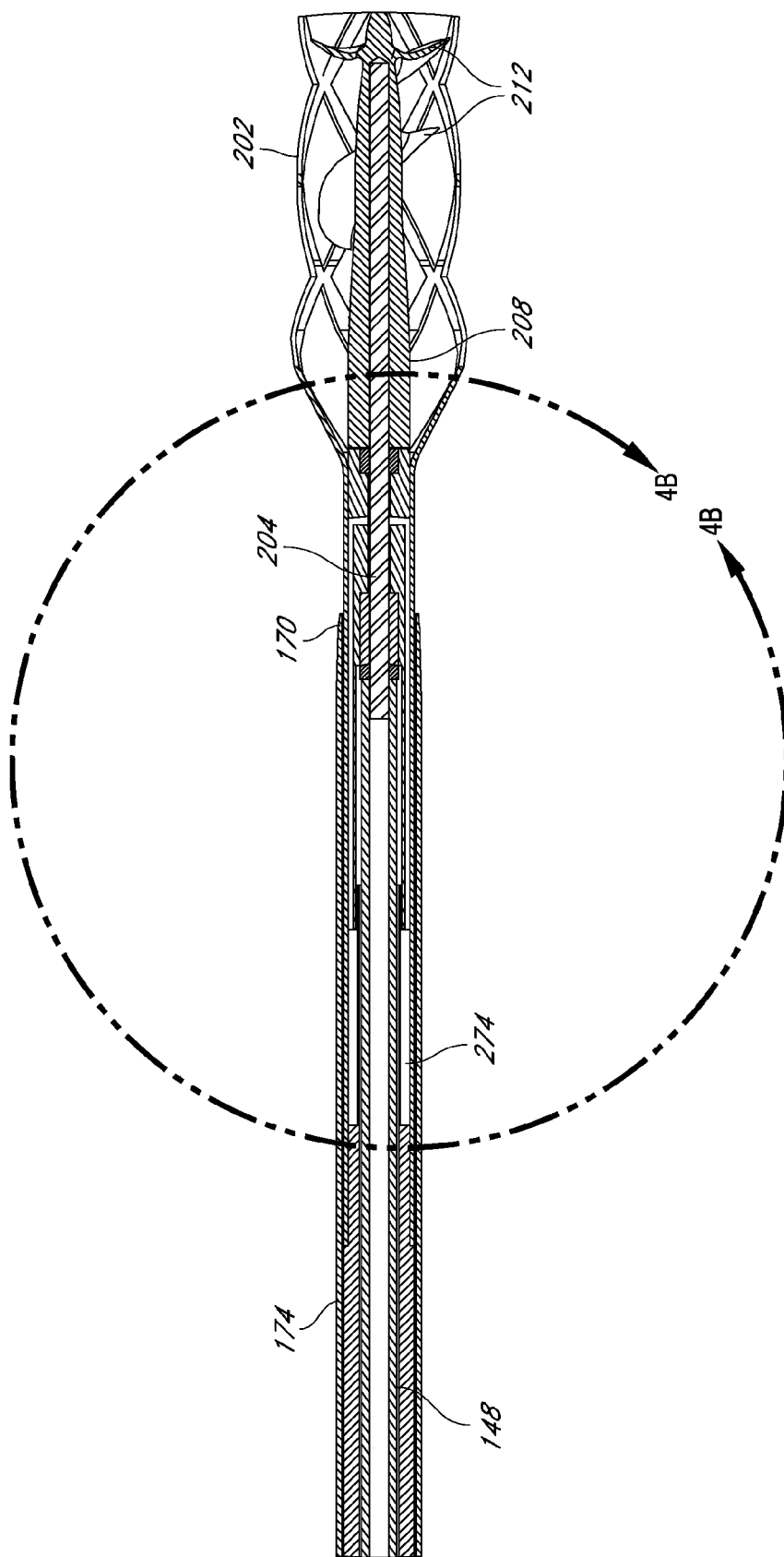


**FIG. 2**

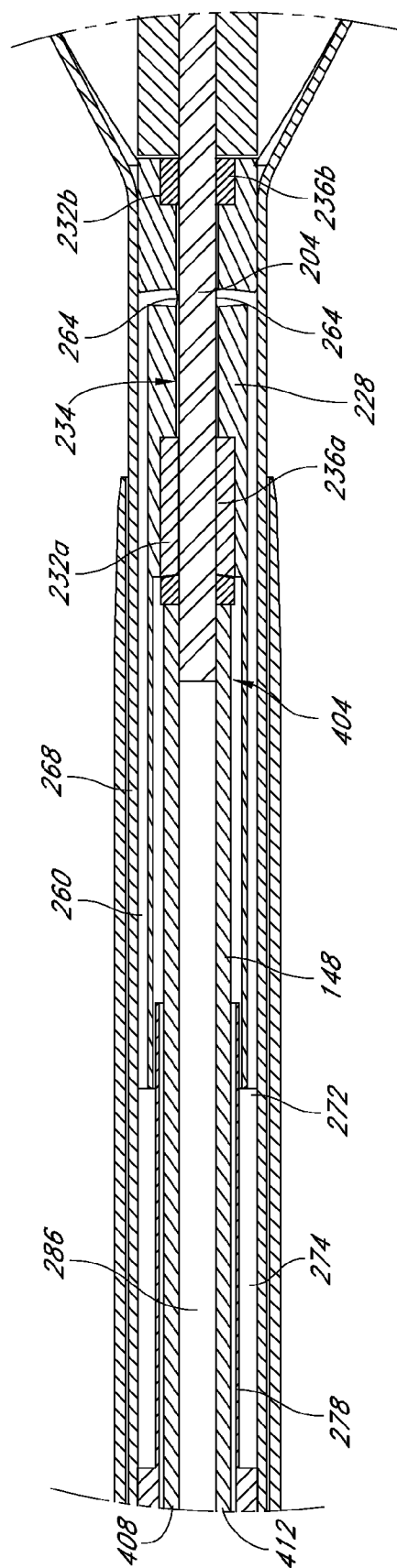




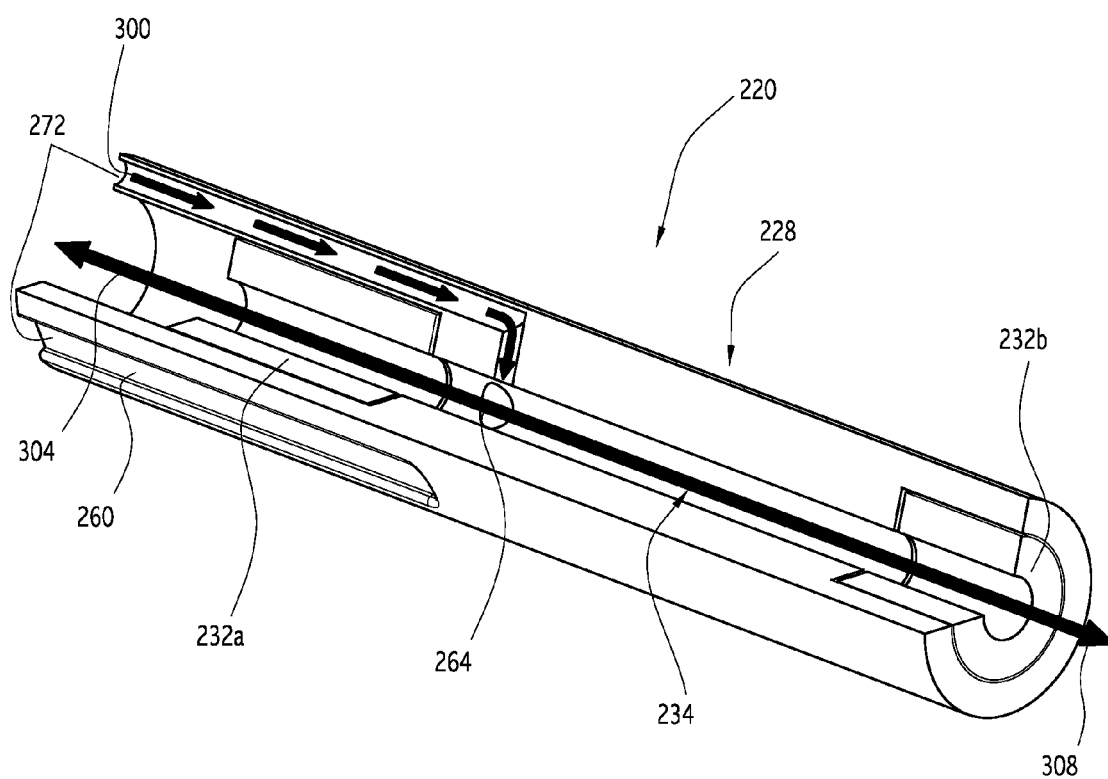
**FIG. 3**



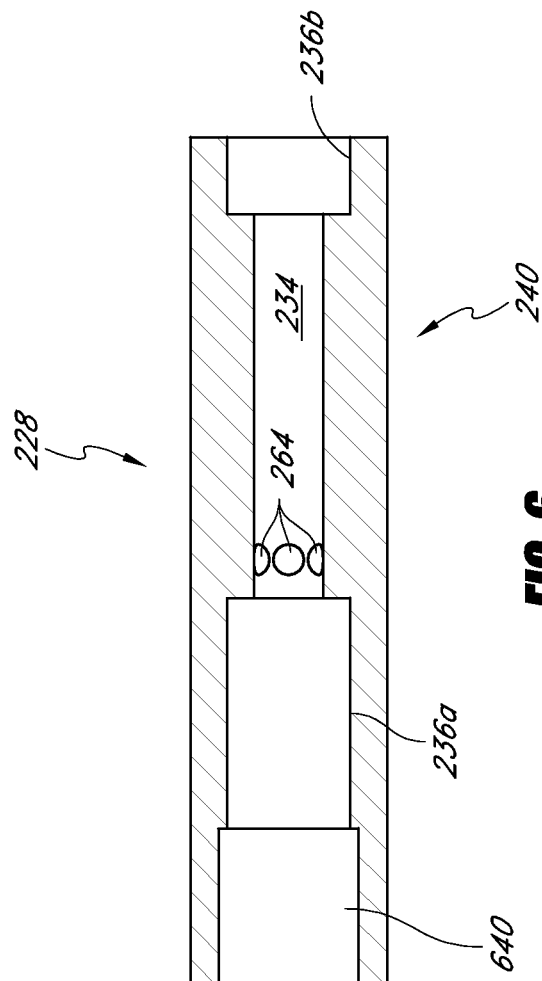
**FIG. 4A**

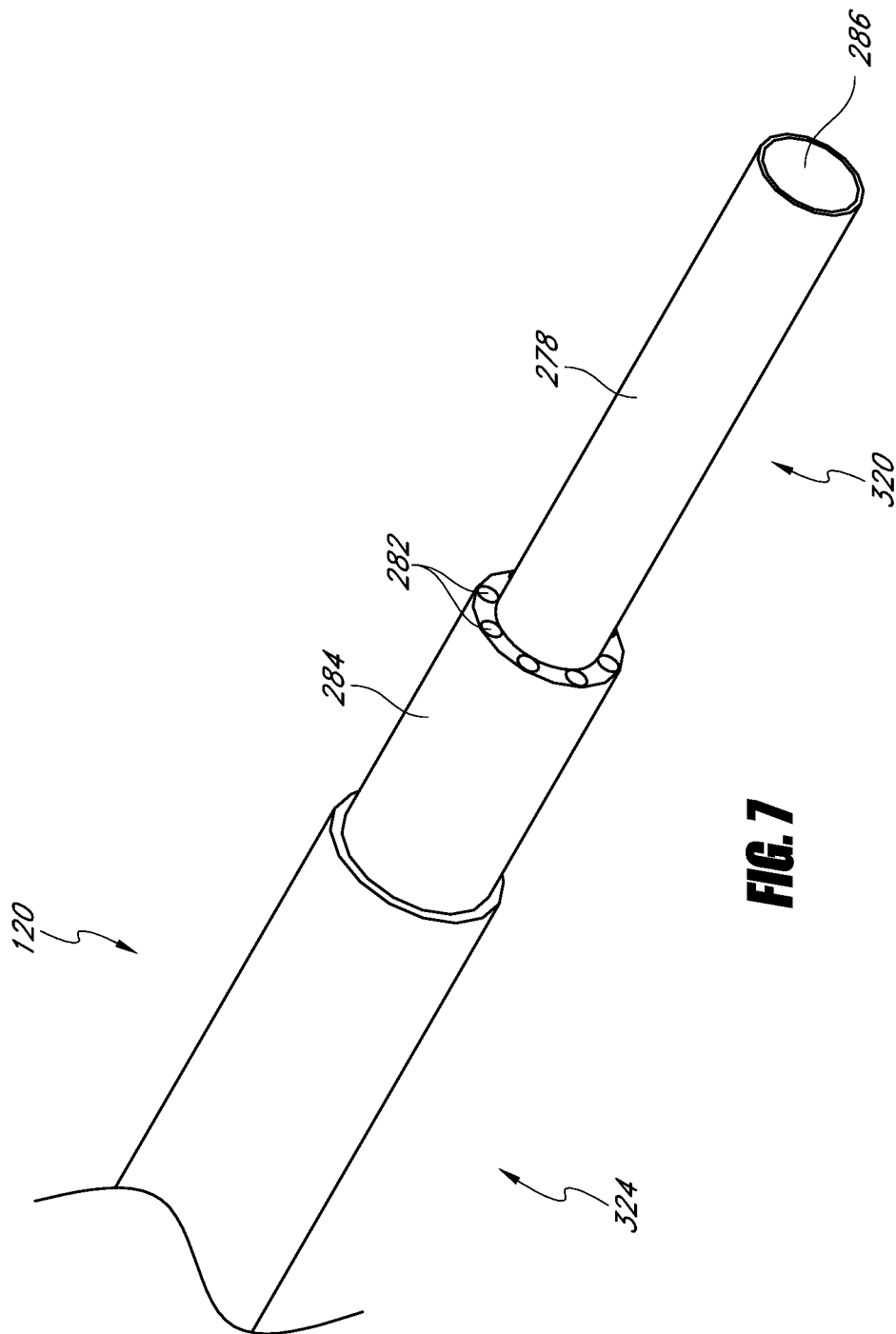


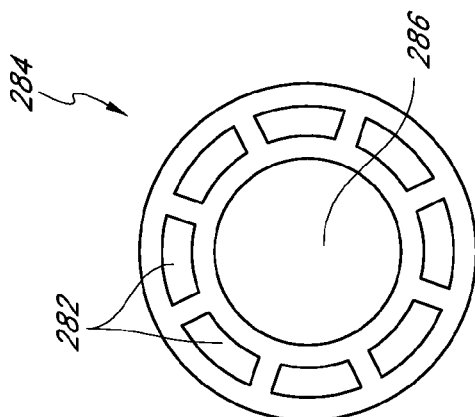
**FIG. 4B**



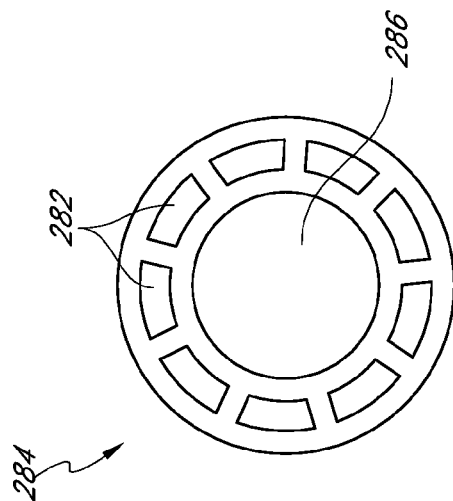
**FIG. 5**



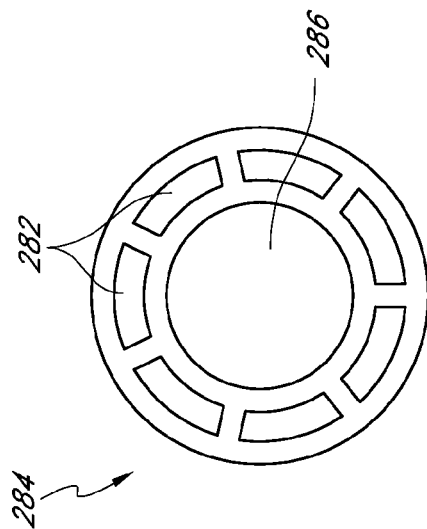




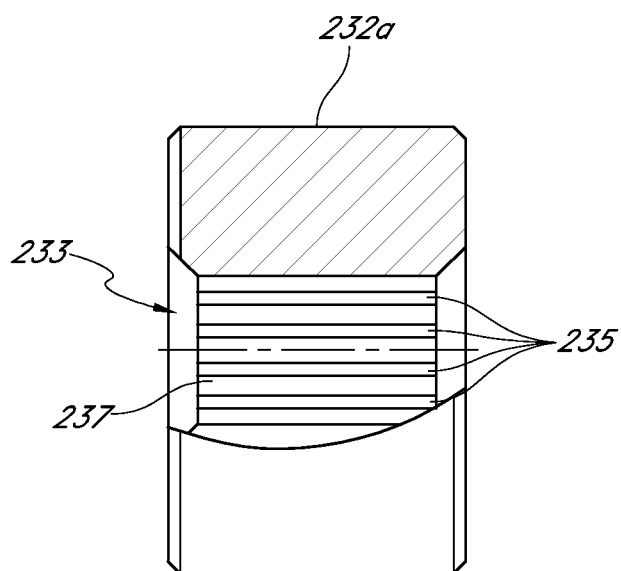
**FIG. 7C**



**FIG. 7B**

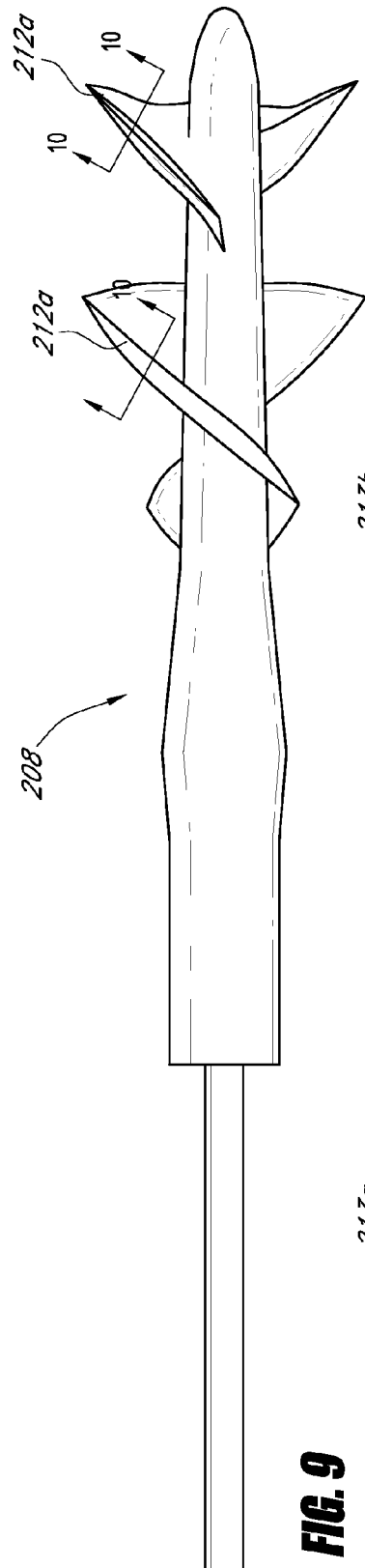


**FIG. 7A**

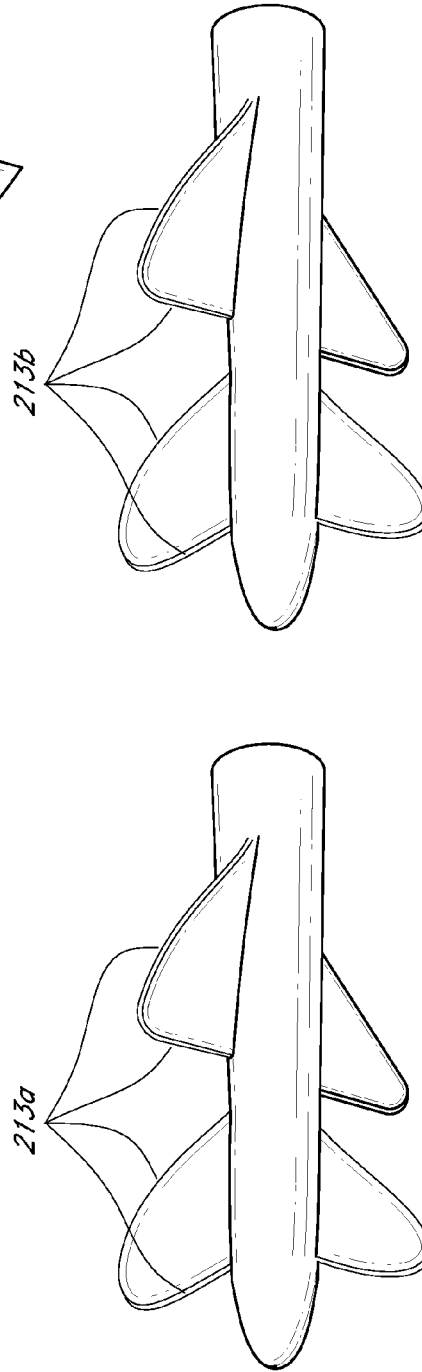


**FIG. 8**





**FIG. 9**



**FIG. 9A**

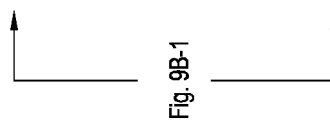
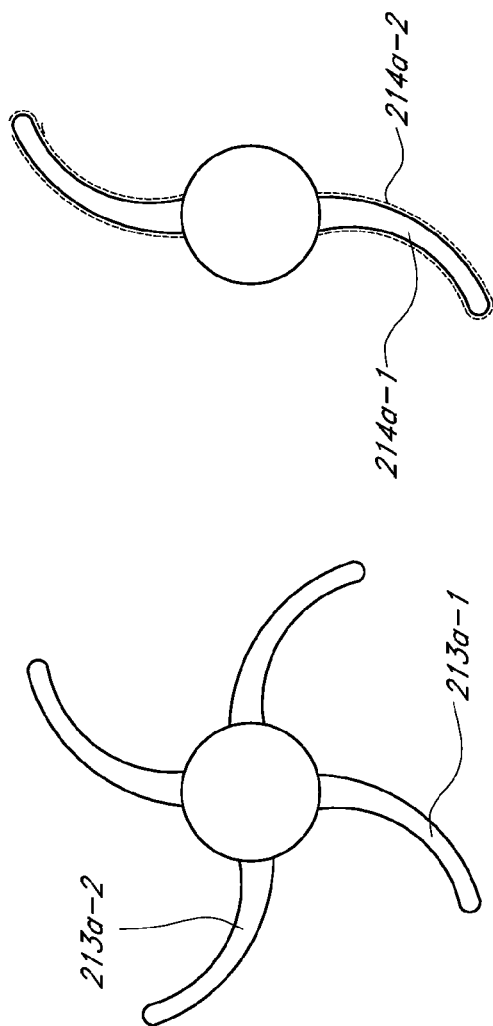
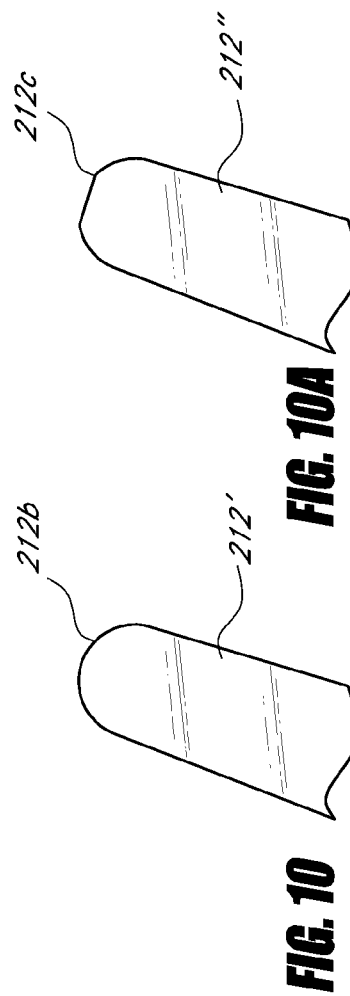


Fig. 9B-1



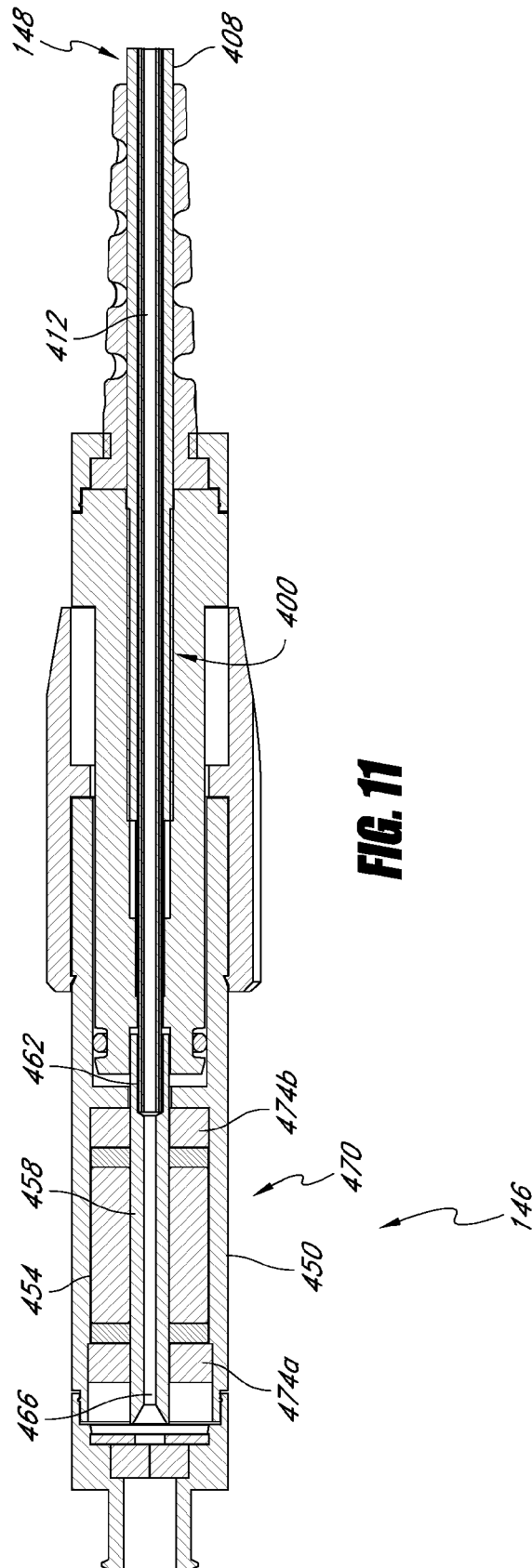
**FIG. 9B-1**

**FIG. 9B-2**

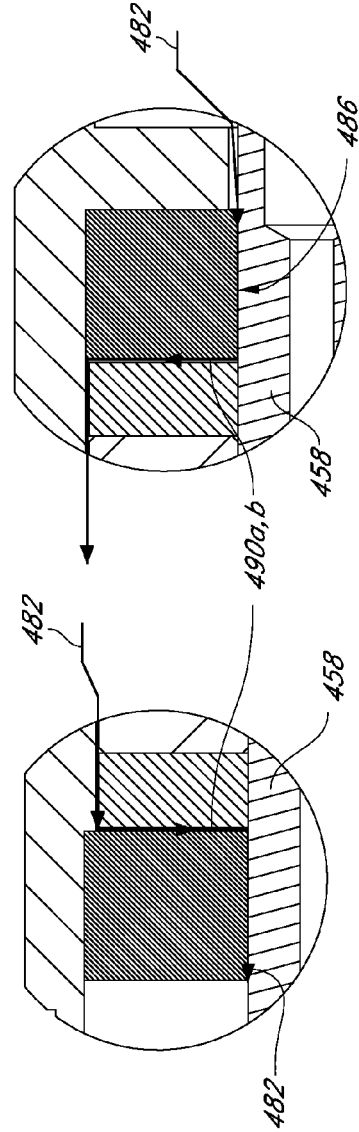
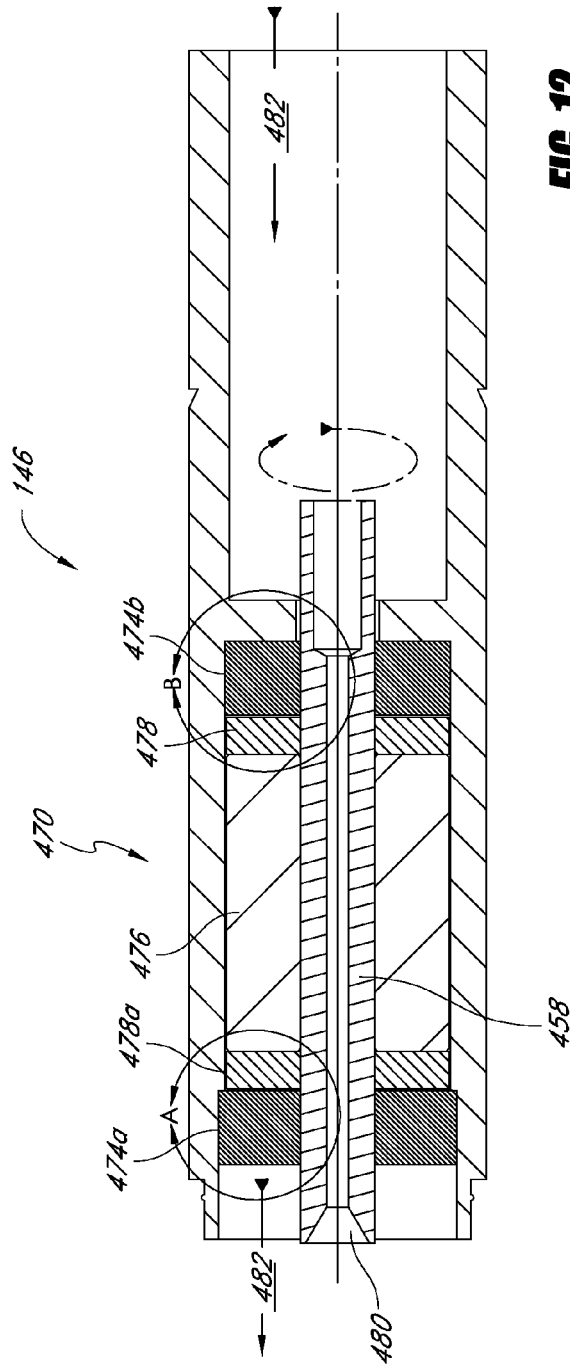


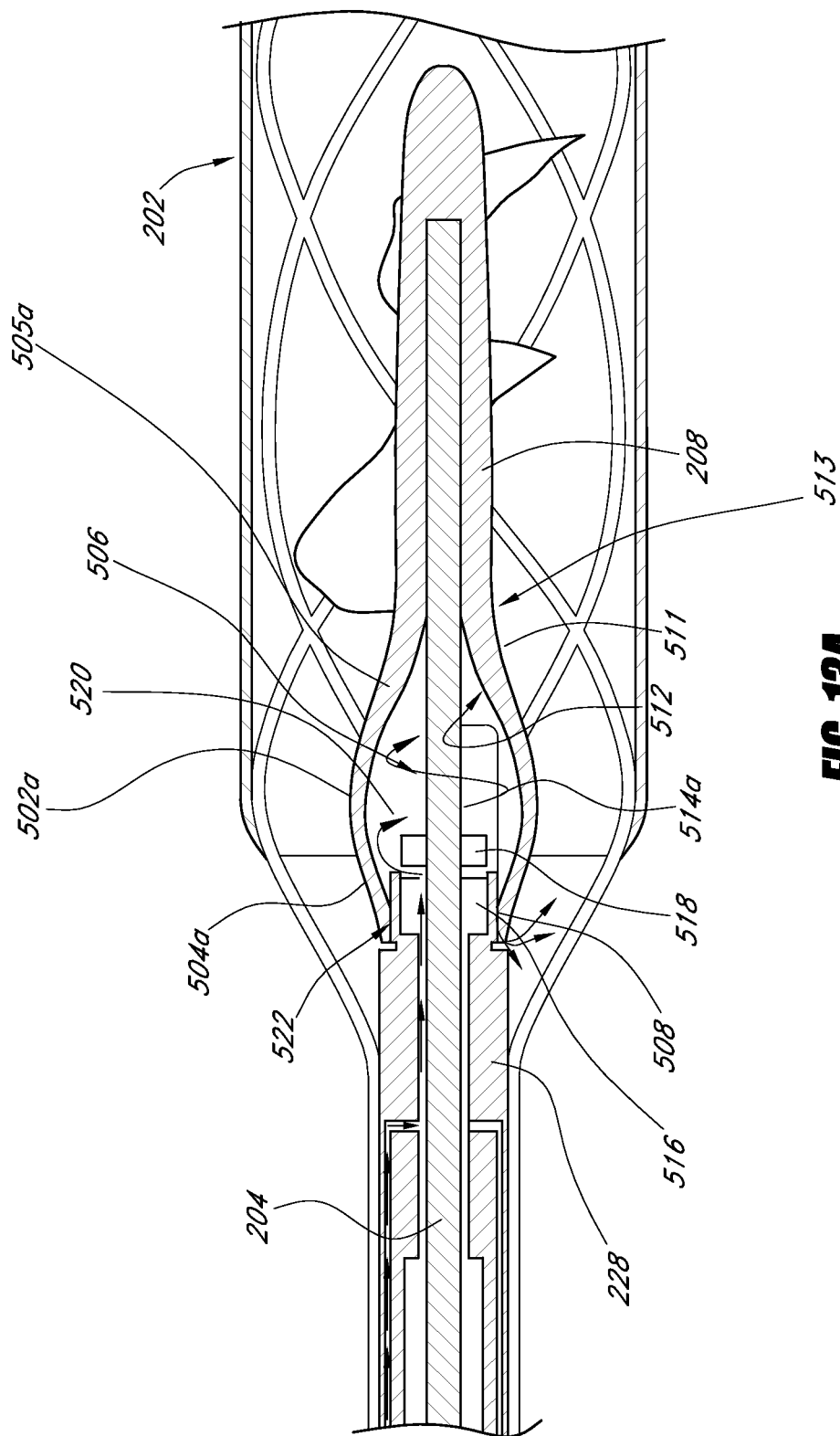
**FIG. 10**

**FIG. 10A**

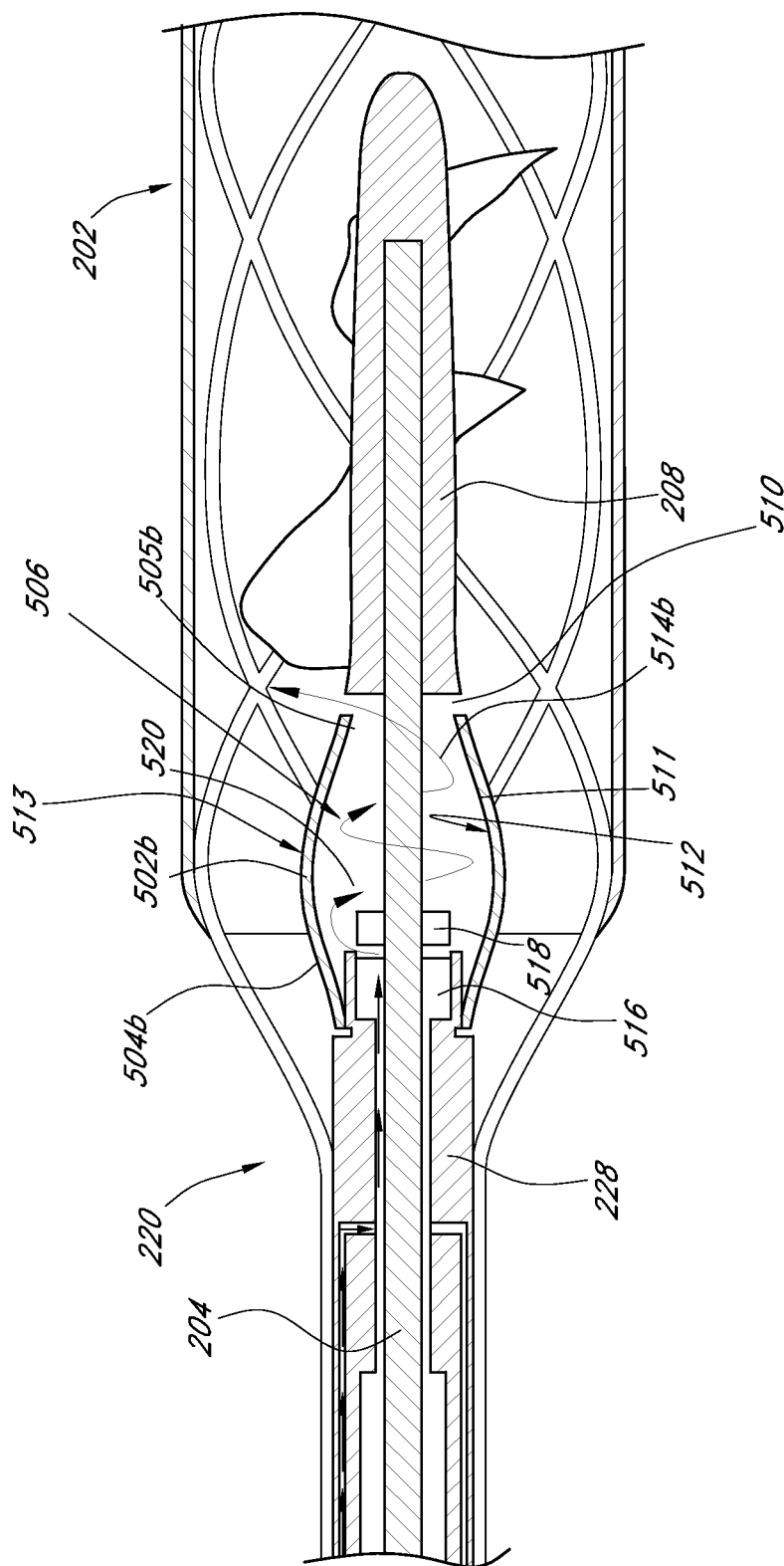


**FIG. 11**

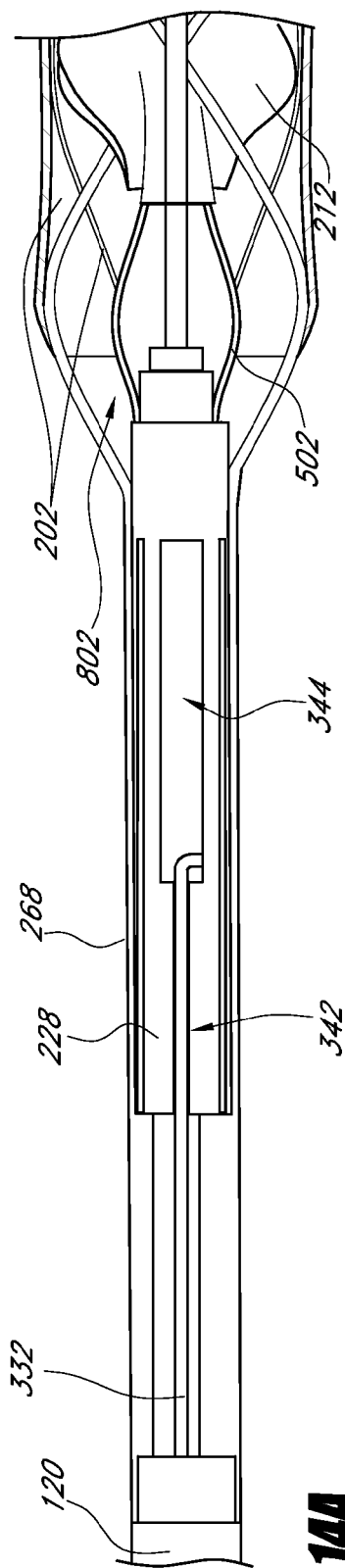




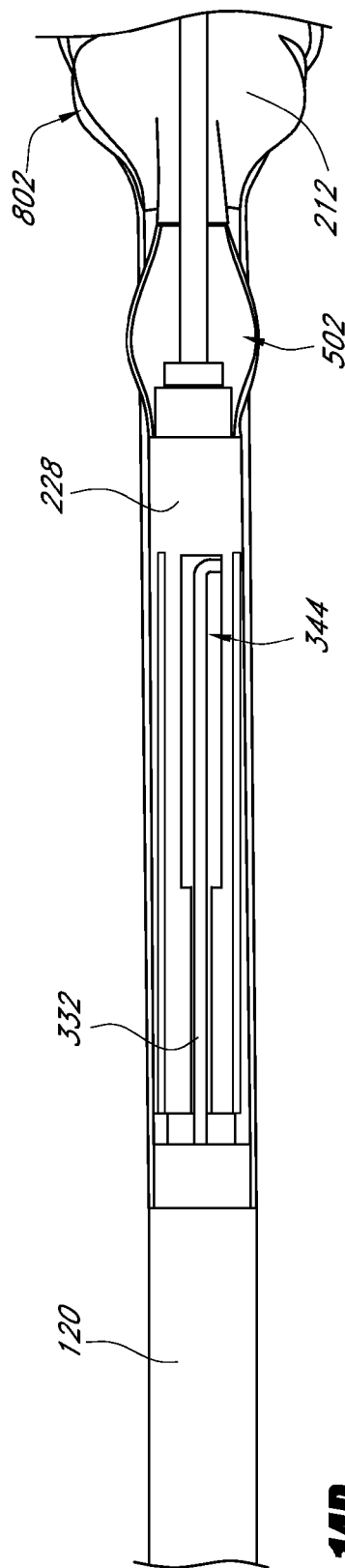
**FIG. 13A**



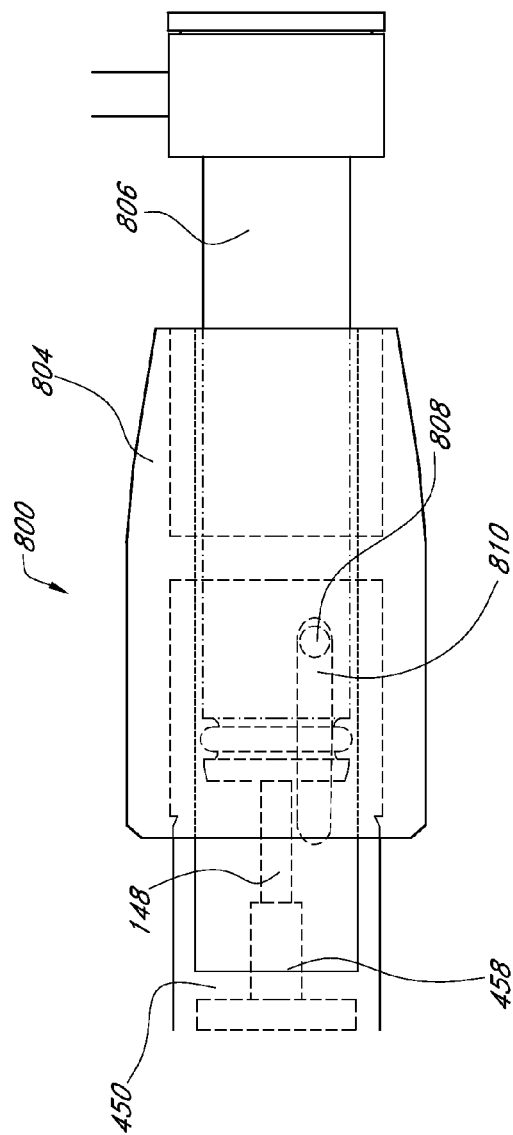
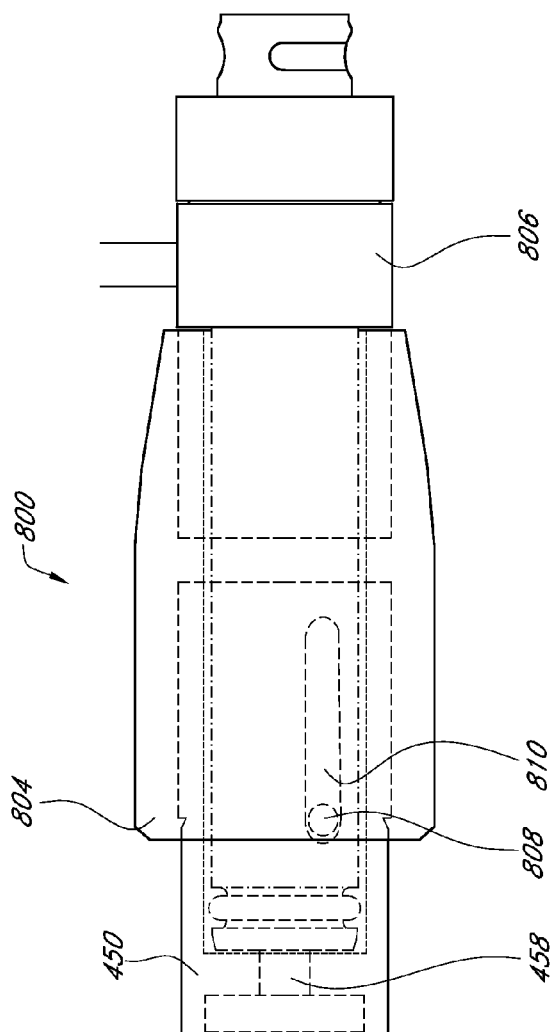
**FIG. 13B**



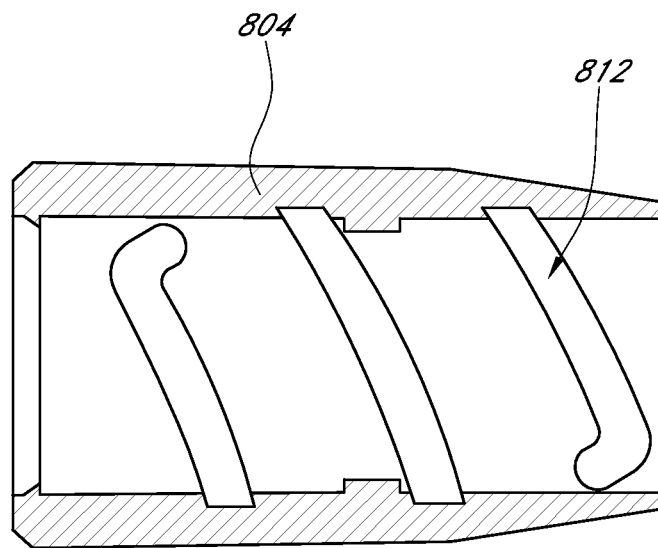
**FIG. 14A**



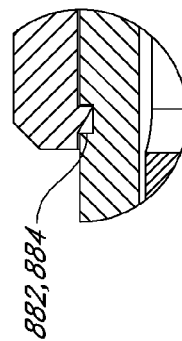
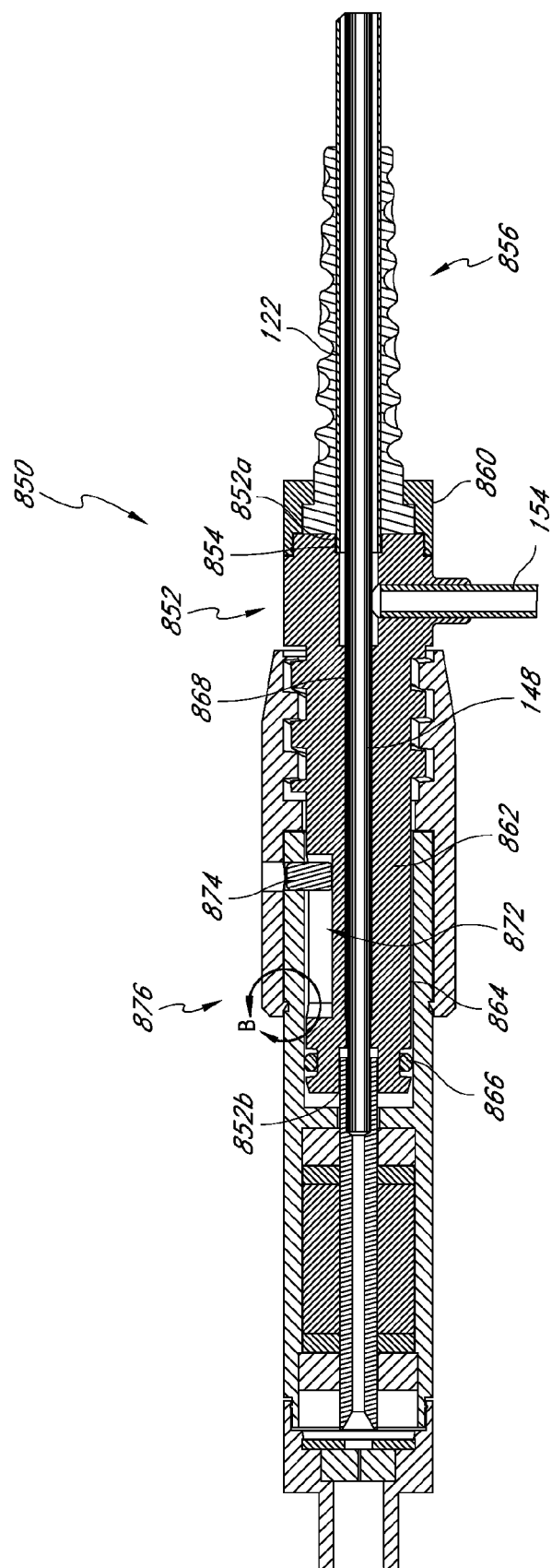
**FIG. 14B**





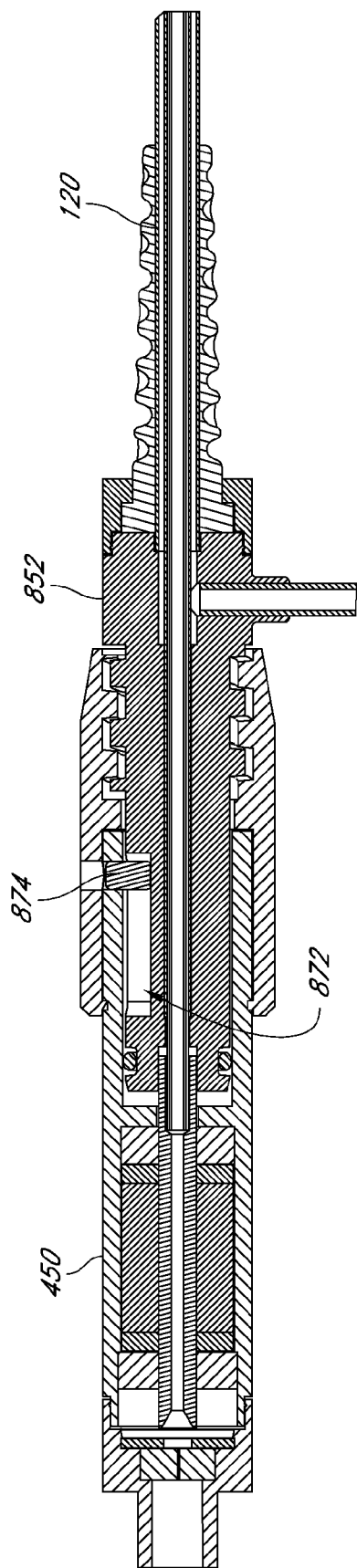


**FIG. 15C**

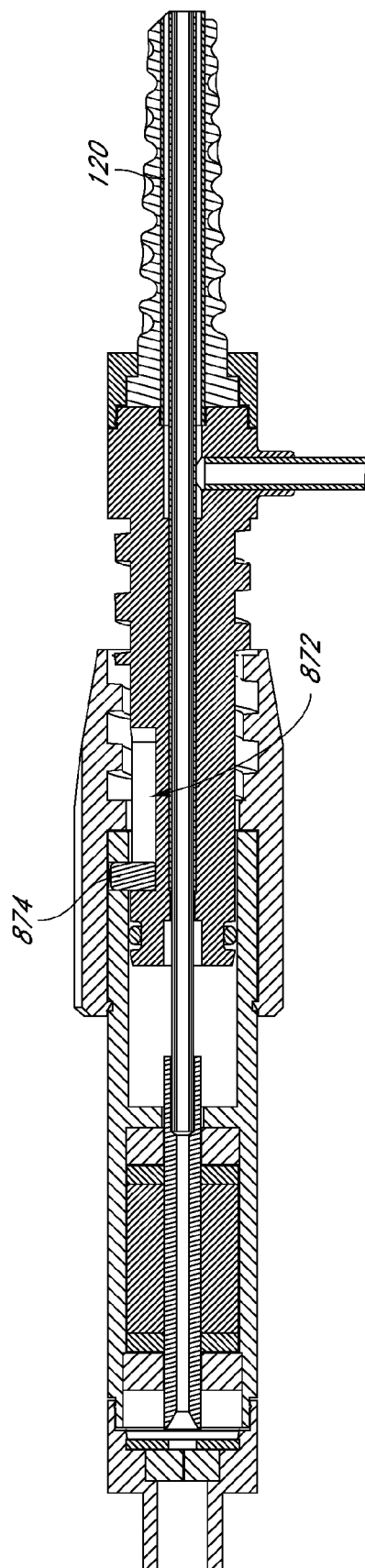


DETAIL B

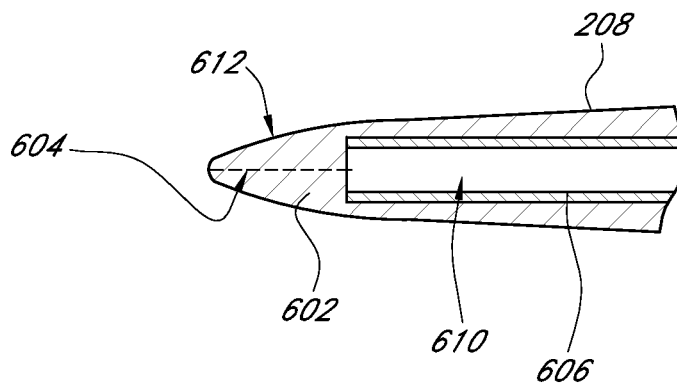
**FIG. 150**



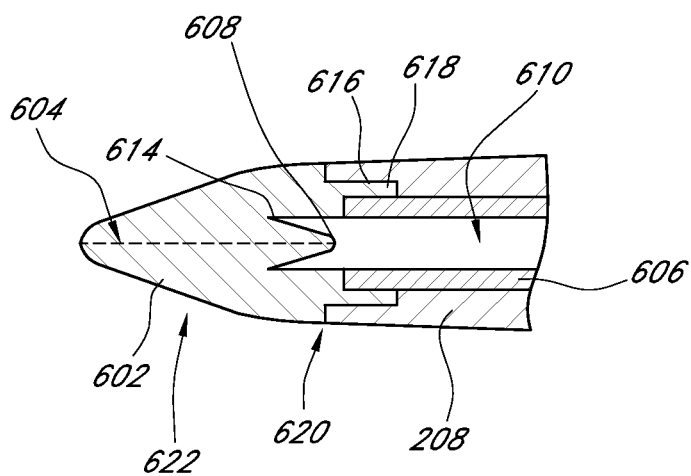
**FIG. 15E**



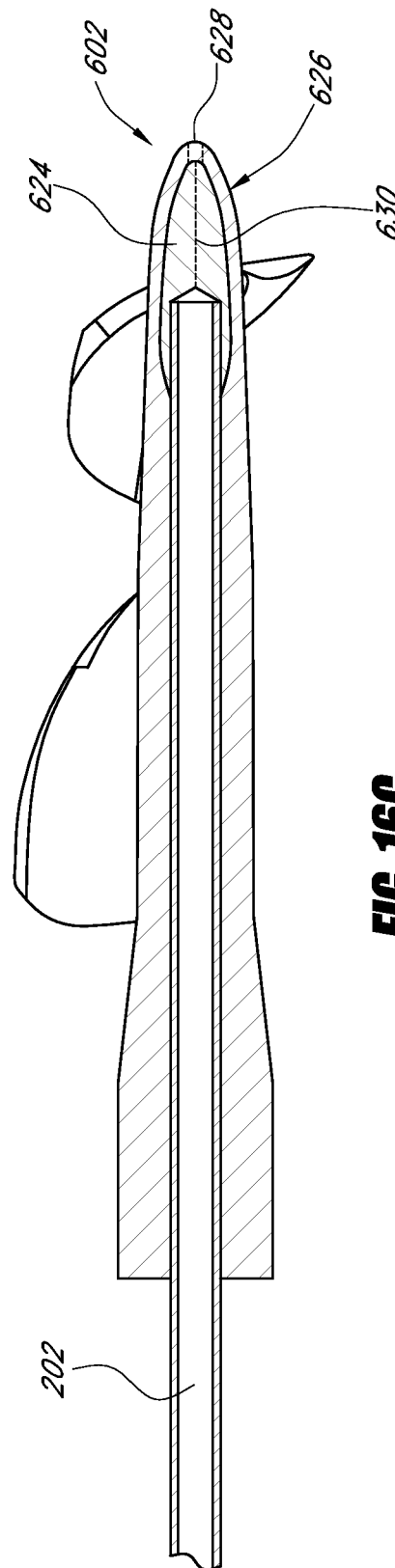
**FIG. 15F**



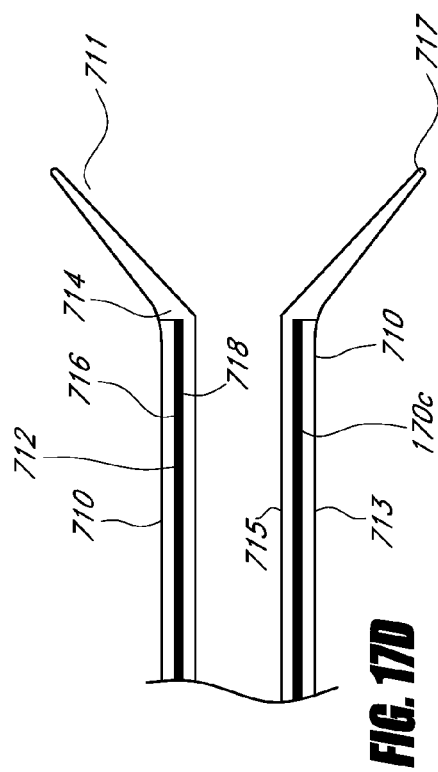
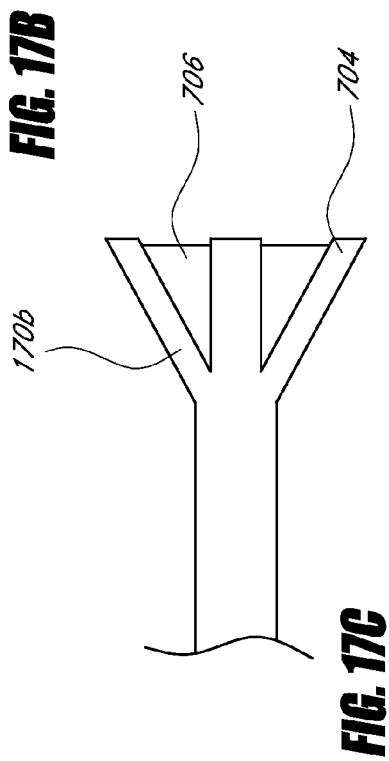
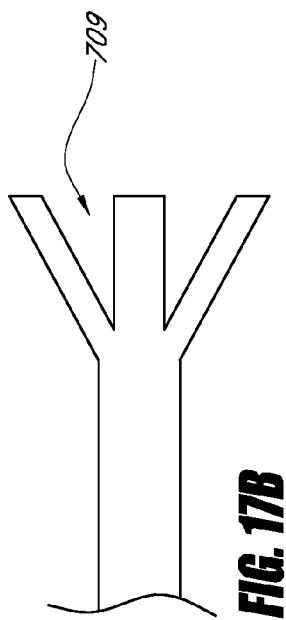
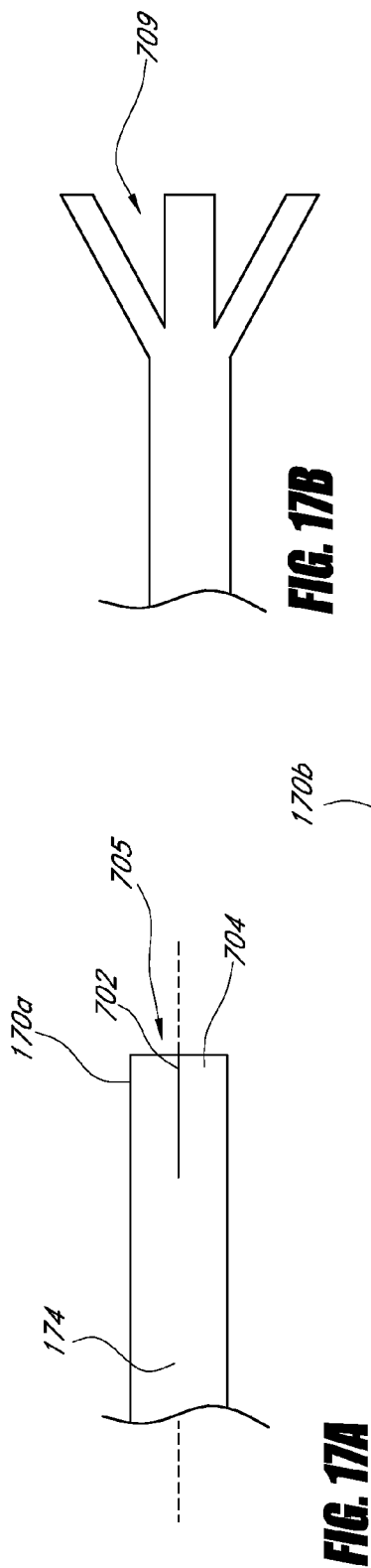
**FIG. 16A**



**FIG. 16B**



**FIG. 16C**



1

**PERCUTANEOUS HEART PUMP****CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims priority to U.S. Provisional Application Ser. No. 61/430,537 filed Jan. 6, 2011 entitled Percutaneous Heart Pump, which is hereby incorporated by reference herein for all purposes.

**BACKGROUND OF THE INVENTION****1. Field of the Invention**

This application is directed to heart pumps that can be applied percutaneously.

**2. Description of the Related Art**

Heart disease is a major health problem that claims many lives per year. After a heart attack, only a small number of patients can be treated with medicines or other non-invasive treatment. However, a significant number of patients can recover from a heart attack or cardiogenic shock if provided with mechanical circulatory support.

In a conventional approach, a blood pump having a fixed cross-section is surgically inserted a heart chamber, such as into the left ventricle of the heart and the aortic arch to assist the pumping function of the heart. Other known applications involve providing for pumping venous blood from the right ventricle to the pulmonary artery for support of the right side of the heart. The object of the surgically inserted pump is to reduce the load on the heart muscle for a period of time, which may be as long as a week, allowing the affected heart muscle to recover and heal. Surgical insertion, however, can cause additional serious stresses in heart failure patients.

Percutaneous insertion of a left ventricular assist device ("LVAD"), a right ventricular assist device ("RVAD") or in some cases a system for both sides of the heart (sometimes called "biVAD") therefore is desired. Conventional fixed cross-section ventricular assist devices designed to provide near full heart flow rate are too large to be advanced percutaneously, e.g., through the femoral artery. There is an urgent need for a pumping device that can be inserted percutaneous and also provide full cardiac rate flows of the left, right, or both the left and right sides of the heart when called for.

**SUMMARY OF THE INVENTION**

In one embodiment, a heart pump is provided that includes a catheter body, a housing, an impeller, and a diffuser. The catheter body includes a proximal end, a distal end, and an elongate body extending therebetween. The housing is coupled with the distal end of the catheter body and comprises a distal opening and a proximal opening. The impeller assembly is coupled with the distal end of the catheter body and positioned within the housing. The diffuser can include a flow directing surface. The diffuser is disposed between the distal end of the catheter body and the impeller. The diffuser is configured to be positioned within the housing and adjacent the proximal opening.

In another embodiment, a heart pump is provided that includes a catheter body comprising a proximal end, a distal end, and an elongate body extending therebetween. The pump also includes an impeller coupled with the distal end of the catheter body and comprising an axial lumen passing through a distal end of the impeller. The impeller comprises a tip positioned at the distal end of the impeller, the tip comprising a resealable member having a resealable path.

2

In another embodiment, a heart pump is provided that comprises a catheter body, an impeller, and a sheath. The catheter body has a proximal end, a distal end, and an elongate structure extending therebetween. The impeller is coupled with the distal end of the catheter body. The sheath is disposed over at least a portion of the distal end of the catheter body. The sheath also has an expandable distal end.

In another embodiment, a catheter assembly is provided that includes a catheter body, an impeller, and a deployment device. The catheter body comprises a proximal end, a distal end, and an elongate structure extending therebetween. The impeller is configured for relative motion in an axial direction, and is located at the distal end of the catheter body. The deployment device is located at the proximal end of the catheter assembly.

**BRIEF DESCRIPTION OF THE DRAWINGS**

A more complete appreciation of the subject matter of the present inventions and the various advantages thereof can be realized by reference to the following detailed description, in which reference is made to the accompanying drawings in which:

FIG. 1 illustrates one embodiment of a heart pump configured for percutaneous application and operation;

FIG. 1A is a plan view of one embodiment of a catheter assembly adapted to be used with the heart pump of FIG. 1;

FIG. 2 is a detail view of a distal portion of the catheter assembly illustrated in FIG. 1A;

FIG. 3 is an exploded view of a portion of an impeller assembly of the catheter assembly of FIG. 1A;

FIG. 4A is a cross-sectional view of a distal portion of the catheter assembly, taken through the section plane 4A-4A shown in FIG. 2;

FIG. 4B is a detail view of the distal portion of the catheter assembly, taken at 4B-4B shown in FIG. 4A;

FIG. 5 is a cross-sectional perspective view of a bearing assembly of the catheter assembly of FIG. 1A;

FIG. 6 is a cross-sectional view of a bearing housing of the bearing assembly of FIG. 5;

FIG. 7 is a perspective view of one embodiment of a catheter body that can be used to house a drive shaft and to convey an infusant to the bearing housing of FIG. 5;

FIGS. 7A-7C show variations of the catheter body of FIG. 7;

FIG. 8 illustrates a surface configuration of one embodiment of a bearing adapted to enhance or control flow of an infusant in the bearing assembly of FIG. 5;

FIG. 9 illustrates one embodiment of an impeller assembly;

FIGS. 9A, 9B-1, 9B-2, 10 and 10A illustrate details of further embodiments of impeller blades;

FIG. 11 is a cross-sectional view of a proximal portion of the catheter assembly, taken through the section plane 11-11 on FIG. 1A;

FIGS. 12, 12A, and 12B are cross-section views similar to that of FIG. 11, illustrating an infusant outflow path;

FIGS. 13A-B are cross-sectional views of two embodiments of a blood pump that includes a diffuser;

FIGS. 14A-B are partial cross-sectional views illustrating one embodiment of a blood pump including a retractable impeller assembly in deployed and retracted configurations, respectively;

FIGS. 15A-B illustrate a deployment device disposed at the proximal end of a catheter assembly illustrated in FIGS. 14A-B in deployed and retracted configurations, respectively;



FIG. 15C is a cross-sectional view of a structure for actuating the deployment device illustrated in FIGS. 15A-B;

FIGS. 15D-F illustrate further embodiments of deployment devices that can actuate the catheter assembly between deployed and retracted configurations;

FIGS. 16A-C are cross-sectional views of three embodiments of a self-sealing impeller tip; and

FIGS. 17A-D are perspective views of variations of a sheath assembly having an expandable distal portion.

A more detailed description of various embodiments of components for heart pumps useful to treat patients experiencing cardiac stress, including acute heart failure, are set forth below.

## DETAILED DESCRIPTION

Major components of heart pumps that can be applied percutaneously to a patient are described below in Section I. Section II describes various structures that facilitate the rotatable support of a cantilevered impeller. Section III describes various structures that facilitate deployment and/or retrieval of one or more components of the distal end 108 of the heart pump 10 within the cardiovascular system. Section IV describes various methods and techniques in connection with specific structures of heart pumps

### I. Overview of Heart Pumps

FIG. 1 illustrates one embodiment of a heart pump 10 that includes a catheter assembly 100 having a proximal end 104 adapted to connect to a motor 14 and a distal end 108 (see FIG. 1A) adapted to be inserted percutaneously into a patient. The motor 14 is connected by a signal line 18 to a control module 22 that provides power and/or control signals to the motor 14. As discussed further below, the heart pump 10 in various embodiments has an infusion system 26 and a patient monitoring system 30.

The infusion system 26 can provide a number of benefits to the heart pump 10 which are discussed below. In one embodiment, the infusion system 26 includes a source of infusant 34, a fluid conduit 38 extending from the infusant source 34 to the proximal end 104 of the catheter assembly 100 and a fluid conduit 42 extending from the proximal end of the catheter assembly 100 to a waste container 46. The flow of infusant to and from the catheter assembly 100 can be by any means, including a gravity system or one or more pumps. In the illustrated embodiment, the infusant source 34 includes an elevated container 50, which may be saline or another infusant as discussed below. Flow from the elevated container 50 can be regulated by a pressure cuff 54 to elevate the pressure of the fluid in the container 50 to increase flow or by a pinch valve 58 or by other means.

The patient monitoring system 30 can be used to monitor the operation of the patient and/or the pump 10. For example, the patient monitoring system 30 can include a user interface 60 coupled with a source of data 64. The data source 64 can include one or more patient conditions sensors, such as pressure sensors 68 that are in pressure communication with the patient and/or operating components within the patient. In one embodiment, the pressure sensors 68 fluidly communicate by a conduit 72 that extends between the sensors and a proximal portion of the catheter assembly 100. The conduit 72 can include a plurality of separable segments and can include a valve 76 to enable or disable the pressure communication to the sensors 68.

The heart pump 10 is adapted to provide an acute or other short-term treatment. A short-term treatment can be for less

than a day or up to several days or weeks in some cases. With certain configurations the pump 10 can be used for a month or more.

The catheter assembly 100 extends between the proximal end 104 and the distal end 108. An impeller assembly 116 disposed at the distal end 108 is configured to pump blood to convey blood from one body cavity to another. In one arrangement, the impeller assembly 116 conveys blood proximally through or along a portion of the catheter assembly 100 to provide assistance to the left ventricle of the heart. In another embodiment, the impeller assembly 116 conveys blood distally through or along a portion of the catheter assembly 100 to provide assistance to the right ventricle of the heart. The heart pump 10 is useful as a heart assist device for treating patients with acute heart failure or other heart maladies. The heart pump 10 also can be used in connection with a surgical treatment to support the patient without providing full cardiovascular bypass. A patient could be supported on the device for longer term with proper controls and design.

The catheter assembly 100 is provided with a low profile configuration for percutaneous insertion. For example, the distal end 108 of the catheter assembly 100 can be configured to have about an 11 French (approximately 3.5 mm) size in a first configuration for insertion and an expanded configuration, such as up to about 21 French (approximately 7 mm), once positioned in the body. The larger size facilitates greater flow rates by the impeller assembly 116 as discussed below.

The catheter assembly 100 is configured to enable the distal end 108 to reach a heart chamber after being inserted initially into a peripheral vessel. For example, the catheter assembly 100 can have a suitable length to reach the left ventricle and sufficient pushability and torquability to traverse the intervening vasculature. The catheter assembly 100 may include a multilumen catheter body 120 that is arranged to facilitate delivery and operation of the impeller assembly 116. Further details concerning various embodiments of the catheter body 120 are discussed below in connection with FIGS. 7-7C.

A drive system is provided to drive an impeller within the impeller assembly 116. The drive system includes a motor 14 and a suitably configured drive controller (not shown) disposed within the control module 22. The motor 14 is in various embodiments is configured to be disposed outside the patient, e.g., adjacent to the proximal end 104 of the catheter assembly 100. In one advantageous embodiment, the drive system employs a magnetic drive arrangement. The motor 14 is arranged to generate magnetic fields that will be sensed by permanent magnets disposed within the proximal end 104 of the catheter assembly 100. This arrangement facilitates very efficient generation of torque used to drive the impeller assembly 116, as discussed below.

Some embodiments described herein could be incorporated into a system in which a motor is miniaturized sufficiently to be inserted into the patient in use, including into the vasculature. Such an embodiment could be operated by disposing control signal lines within the proximal portion of the catheter body 120. Also, it may be useful to provide the capability to measure blood pressure at the distal end 108 using a device disposed at the proximal end 104. For example, a pressure sensor at the distal end can communicate with a device outside the patient through a lumen of the catheter body 120. Various details of these optional features are described in U.S. Pat. No. 7,070,555, which is incorporated by reference herein for all purposes and in its entirety.

In another embodiment, a mechanical interface can be provided between the motor and the proximal end 104 of the catheter assembly 100. The mechanical interface can be

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between the motor **14** and a drive shaft positioned at the proximal end of the catheter assembly **100**.

A torque coupling system is provided for transferring torque generated by the drive system to the impeller assembly **116**. The torque coupling system is discussed further in Section II(C)—Torque Coupling System (as discussed below), but in general can include magnetic interface between the motor **14** and a drive assembly **146** disposed at the proximal end **104** of the catheter assembly **100**. The drive assembly **146** is coupled with a proximal end of an elongate drive shaft **148** in one embodiment. The drive shaft **148** extends between the drive assembly **146** and the impeller assembly **116**. A distal portion of the drive shaft **148** is coupled with the impeller assembly **116** as discussed below in connection with one embodiment illustrated in FIGS. **4A** and **4B**. FIG. **11** shows one manner of coupling the proximal end of the drive shaft **148** with the drive assembly **146**.

As discussed above, the heart pump **10** may also include an infusion system **26**. FIG. **1A** shows that the infusion system **26** can include an infusion inflow assembly **150** provided adjacent to the proximal end **104** in one embodiment. The infusion assembly **150** can be one component of an infusion system that is configured to convey one or more fluids within the catheter assembly **100**. The fluids can be conveyed distally within the catheter assembly **100**, e.g., within the catheter body **120**, to facilitate operation of the impeller assembly **116**, some aspect of a treatment, or both. In one embodiment, the infusion system is configured to convey a lubricant, which can be saline, glucose, lactated Ringer's solution, acetated Ringer's solution, Hartmann's solution (e.g., including compound sodium lactate), and D5W dextrose solution. In another embodiment, the infusion system is configured to convey a medication, or a substance that both acts as lubricant and medication. As sometimes used herein "infusant" is intended to be a broad term that includes any fluid or other matter that provides performance enhancement of a component of the heart pump **10** or therapeutic benefit, and can be wholly or partly extracted from the system during or after operation of the pump.

In one embodiment, the infusion inflow assembly **150** includes a catheter body **154** having a luer or other suitable connector **158** disposed at a proximal end thereof and an inflow port in fluid communication with one or more lumens within the catheter assembly **100**. A lumen extending through the catheter body **154** is adapted to be fluidly coupled with a fluid source connected to the connector **158** to deliver the fluid into the catheter assembly **100** and through one or more flow paths as discussed below in connection with FIGS. **4A**, **4B**, and **7-7C**.

FIGS. **1A** and **12** show that the catheter assembly **100** in various embodiments also includes an outlet positioned at a location that is outside the patient when the heart pump **10** is in use to allow infusant to be removed from the pump and from the patient during or after the treatment. The outlet can be fluidly coupled with an infusant return flow path in the catheter body **120** through a fluid port **144** disposed at the proximal end **104**.

The catheter assembly **100** can also include a sheath assembly **162** configured to constrain the impeller assembly **116** in a low profile configuration in a first state and to permit the impeller assembly **116** to expand to the enlarged configuration in a second state. The sheath assembly **162** has a proximal end **166**, a distal end **170**, and an elongate body **174** extending therebetween. In one embodiment, the elongate body **174** has a lumen extending between the proximal and distal ends **166**, **170**, the lumen being configured to be slidably disposed over the catheter body **120**. The arrangement

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permits the sheath assembly **162** to be actuated between an advanced position and a retracted position. The retracted position is one example of a second state enabling the impeller assembly **116** to expand to an enlarged configuration. The advanced position is one example of a first state that enables the impeller assembly **116** to be collapsed to the low profile configuration. In some embodiments, a luer **102** or other suitable connector is in fluid communication with the proximal end **166** of the sheath assembly **162**. The luer **102** can be configured to deliver fluids to the catheter assembly **100**, such as priming fluid, infusant, or any other suitable fluid.

FIG. **1A** illustrates a retracted position, in which the distal end **170** of the elongate body **174** is at a position proximal of the impeller assembly **116**. In an advanced position, the distal end **170** of the elongate body **174** is positioned distal of at least a portion of the impeller assembly **116**. The sheath assembly **162** can be configured such that distal advancement of the distal end **170** over the impeller assembly **116** actuates the impeller assembly **116** from an enlarged state to a more compact state (or low profile configuration), e.g., causing a change from the second state to the first state, as discussed above.

FIGS. **4A** & **4B** show the elongate body **174** as a single layer structure from the inner surface to the outer surface thereof. In another embodiment, the elongate body **174** has a multilayer construction. In one arrangement, the elongate body **174** has a first layer that is exposed to the catheter body **120** and a second layer exposed that corresponds to an outer surface of the catheter assembly **100**. A third layer can be disposed between the first and second layers to reinforce the elongate body **174**, particularly adjacent to the distal end thereof to facilitate collapse of the impeller assembly **116**. In another construction, a reinforcing structure can be embedded in an otherwise continuous tubular structure forming the elongate body **174**. For example, in some embodiments, the elongate body **174** can be reinforced with a metallic coil.

FIG. **2** show that an impeller housing **202** is disposed at the distal end **108**. The impeller housing **202** can be considered part of the impeller assembly **116** in that it houses an impeller and provides clearance between the impeller and the anatomy to prevent any harmful interactions therebetween. The housing **202** and the impeller are also carefully integrated to maintain an appropriate flow regime, e.g., from distal to proximal or from proximal to distal within the housing.

FIGS. **1A** and **2** also show that the distal end **108** of the catheter assembly **100** includes an atraumatic tip **182** disposed distal of the impeller assembly **116** in one embodiment. FIG. **1A** shows that the atraumatic tip **182** can have an arcuate configuration such that interactions with the vasculature are minimally traumatic. The tip **182** can also be configured as a positioning member. In particular, the tip **182** can be rigid enough to help in positioning the impeller assembly **116** relative to the anatomy. In one embodiment, the tip **182** is rigid enough that when it is urged against a heart structure such as the ventricle wall, a tactile feedback is provided to the clinician indicating that the impeller assembly **182** is properly positioned against the heart structure.

## II. Impeller Rotation and Support

The impeller assembly **116** can take any suitable form, but in various embodiments includes an impeller **200** adapted to move a fluid such as blood from an inlet to an outlet of the catheter assembly **100**. In certain embodiments the impeller **200** can be cantilevered or otherwise supported for rotation primarily at one end.

FIG. 3 shows that the impeller **200** includes a shaft **204**, a central body or hub **208**, and one or more blades **212**.

The shaft **204** and hub **208** can be joined in any suitable fashion, such as by embedding a distal portion of the shaft within the hub **208**. The blades **212** can be spaced out proximal to distal along the axis of the shaft. In some embodiments, the blades **212** are provided in blade rows. FIG. 9 shows that the distal end of the shaft **204** can extend at least to an axial position corresponding to one of the blade rows. In some embodiments, the shaft **204** can be solid. In other embodiments, the shaft **204** has a lumen extending axially through the hub so that a guidewire can be passed through the catheter assembly **100**. Details of variations with a lumen are discussed further in U.S. application Ser. No. 12/829,359, filed Jul. 1, 2010, titled Blood Pump With Expandable Cannula, which is hereby incorporated by reference herein in its entirety and for all purposes.

#### A. Infusant Delivery and Removal System

The operation and duty cycle of the impeller assembly **116** can be lengthened by providing a hydrodynamic bearing for supporting the shaft **204**. A hydrodynamic bearing can be supported by a lubricant, such as isotonic saline, which can be delivered in a continuous flow. The lubricant can be delivered through the infusion system to an outside surface of the shaft **204**. The infusant may be directed onto the shaft from a radially outward location. In some arrangements, the lubricant flow is controlled such that of a total lubricant volume introduced into the proximal end of the cannula, a first portion of the total volume of the lubricant flows proximally along the shaft **204**. In some embodiments, a second portion of the total volume flows distally along the shaft, the first volume being different from the second volume. The second portion of the total volume can be substantially equal to the total volume introduced into the proximal end of the cannula less the first volume.

FIGS. 3 to 8 show various structures for providing rotational support of a proximal portion of the shaft **204** within the distal portion of the catheter assembly **100**. For example, as shown in FIG. 3, a bearing assembly **220** can be disposed at a distal end **224** of the multilumen catheter body **120**. In one embodiment, the bearing assembly **224** includes a housing **228** (as shown in FIG. 4B) and one or more bearings configured to support the proximal portion of the shaft **204**. The bearing assembly **224**, as illustrated in more detail in FIG. 4B, includes a plurality of bearings **232a**, **232b** disposed within the bearing housing **228**. Various materials that can be used for the bearings are discussed below.

FIG. 6 shows that the bearing housing **228** has a lumen **234** extending therethrough with a proximal enlarged portion **236a** and a distal enlarged portion **236b**. The housing **228** comprises a shoulder defining a narrow portion **240** of the lumen **234** disposed between the enlarged portions **236a**, **236b**. The first and second bearings **232a**, **232b** can be disposed within the enlarged portions **236a**, **236b** of the bearing housing **228**.

In one arrangement, the proximal end of the shaft **204** (e.g., as shown in FIG. 4A) is received in and extends proximally of the second bearing **232b**. In some embodiments there can be one bearing (e.g., only bearing **232a**), while in other embodiments both bearings **232a** and **232b** can be used. In some embodiments, the bearing(s), e.g., bearings **232a** and/or **232b**, can be friction fit or interference fit onto the impeller shaft **204**. Accordingly, the shaft **204** can be supported for rotation by the bearings **232a**, **232b** as well as in the narrow portion **240** of the housing **228**. In embodiments where the

bearing(s) **232a**, **232b** are friction or interference fit onto the shaft, the bearing(s) **232a**, **232b** can be configured to rotate with the shaft **204** relative to the bearing housing **228**. Further, the bearing(s) **232a**, **232b** can have a relatively large clearance with the bearing housing **228**. The clearance between the shaft **204** and the bearing housing **228**, at regions that are not coupled with the bearing, can be in the range of about 0.0005 to about 0.001 inch. In certain embodiments, the clearance can be within a larger range, such as at least about 0.0005 inches, about 0.001 inches or up to about 0.005 inches. In embodiments with multiple bearing(s) **232a**, **232b**, the clearance can be different for the bearings **232a**, **232b**, such as providing a larger clearance at the proximal bearing **232a**.

In other embodiments, such as in FIG. 5, the bearing(s) **232a**, **232b** may not be friction or interference fit onto the shaft **204**. In these embodiments, the bearing(s) **232a**, **232b** may be disposed within the bearing housing **228**, for example by an interference or press fit. The shaft **204** may then rotate with respect to the bearing(s) **232a**, **232b**, and there can be a clearance between the shaft **204** and the bearing(s) **232a**, **232b**. The clearance between the shaft **204** and the bearings **232a**, **232b** can be in the range of about 0.0005 to about 0.001 inch. In certain embodiments, the clearance can be within a larger range, such as at least about 0.0005 inches, about 0.001 inches or up to about 0.005 inches. The clearance can be different for the bearings **232a**, **232b**, such as providing a larger clearance at the proximal bearing **232a**. In certain embodiments, the bearing housing **228** may provide a thrust surface for bearing axial loads. In other embodiments, there may be other bearings located either distally or proximally of the bearing housing **228** that are configured to bear axial loads. In other embodiments, the fit between the bearings **232a**, **232b** and the shaft **204** can be tight, which can also assist in bearing axial loads in some aspects.

At least the proximal portion of the shaft **204** can be made of a material that will not corrode or otherwise be made to be inert when immersed in the lubricant or other infusant. The material may be one that will not corrode in isotonic saline. Suitable materials may include a wide variety of metals, including alloys, and at least saline-resistant stainless steel and nickel-based alloys. Also, the shaft **204** could be made as a composite to include advantageous properties of a plurality of materials. In some cases the shaft **204** could be formed as a polymer. The class of polymers selected would include those that can form a shaft **204** of a certain stiffness suitable in this application. For example, polycarbonate or PEEK could be used. In certain configurations, the polycarbonate, PEEK, or other suitable polymer can provide enhanced performance by being combined with a second material or structure. A glass or carbon filled polycarbonate or other stiff polymer could also be used.

As discussed above, a hydrodynamic bearing between the shaft **204** and the bearings **232a**, **232b** may be utilized in various embodiments. In one such arrangement, a continuously replenished fluid film is provided at least between the inner wall of the bearing housing and an adjacent moving structure, such as the impeller shaft or an outer surface of a bearing. For example, the bearing housing **228** can be configured to permit a lubricant to be delivered therethrough into the lumen **234**. The bearing housing **232** can include a plurality of channels **260** disposed therein extending proximally from a plurality of ports **264** located at the narrow portion **240** of the housing **228**. Each port **264** can communicate with one of the channels **260** to provide fluid communication into the lumen **234**.

As shown in FIG. 5, the channels **260** can be formed in the wall of the housing **228**. In one embodiment, the channels **260**

are formed as open depressions, e.g., as flutes, extending along the housing 228. In this embodiment, the channels 260 can be enclosed by a separate structure, such as a separate outer sleeve, that is disposed around the housing 228. FIG. 4B shows that a proximal portion 268 of the impeller housing 202 can be sized to tightly fit over the outer surface of the bearing housing 228, enclosing the radially outward portion of the channels 260. In this arrangement, at least a portion of a flow path is formed between an outer surface of the bearing housing 232 and a separate outer sleeve.

Fluid communication between the port 264 in the bearing housing 228 and the infusion inflow assembly 150 can be by any suitable combination of lumens within the catheter assembly 100. For example, in one embodiment, each of the channels 260 has a proximal port 272 that communicates with an annular space 274 formed in the catheter assembly 100. The annular space 274 can be formed between a plurality of separate overlaid structures in the catheter assembly 100. FIGS. 4A and 4B show that the annular space 274 is formed between an outer surface 278 of the multilumen catheter body 120 and an inner surface of the proximal length 268 of the housing 202.

Fluid communication is provided in the catheter assembly 100 between the space 274 and the infusion inflow assembly 150. For example, a plurality of lumens 282 formed in the multi-lumen catheter body 120 can be dispersed circumferentially about the catheter body 120 at a peripheral circumferential region 284, as illustrated in FIGS. 7-7C. The peripheral position of the lumens 282 enables a central area of the catheter body 120 to be dedicated to a central lumen 286. By providing a plurality of smaller lumens 282 located at the periphery, a relatively large flow rate can be delivered through a relatively small circumferential band (when considered in cross-section) of the catheter body 120. Each of the lumen 282 has a distal port 290 that communicates with the space 274.

A proximal portion of the lumens 282 can take any suitable form. For example, the lumens 282 can communicate at their proximal end with a flow diverting structure (not shown) that is in fluid communication with the infusion inflow assembly 150. As described herein, in some embodiments the lumen 282 can be disposed circumferentially about the central lumen 286. The catheter assembly 100 can include a flow diverting structure or connector, e.g., disposed about the proximal end of the catheter body 120 that is configured to divert the infusant into the lumens 282 for distally directed flow therein. In other embodiments, the catheter assembly 120 can include a flow diverting structure disposed adjacent the distal end thereof that is configured to divert the infusant into the lumens 282 from the central lumen 286 for proximally directed flow in the lumens 282.

FIG. 5 includes arrows that illustrate the flow of infusant into the bearing assembly 220. In one arrangement, the inflow of infusant is indicated by an arrow 300 which is shown pointing distally within one of the channels 260 of the bearing housing 228. The infusant flow enters the bearing housing through the ports 264. Although flow is shown in one channel 260, corresponding flow may be provided in each of a plurality of channels 260 disposed around the central lumen 234. An arrow 304 illustrates that at least a portion of the infusant delivered through the port 264 may flow generally proximally within the bearing housing 228. An arrow 308 illustrates that at least a portion of the infusant delivered through the port 264 may flow generally distally within the bearing housing 228.

FIG. 5 illustrates the arrows 304, 308 as proximally and distally directed, respectively. However, the high speed rotation of the impeller shaft 204 within the housing 228 will

create a thin film of lubricant spacing the impeller shaft 204 from the surfaces of the bearings 232a, 232b. This thin film will extend all the way around the shaft 204 and thus each portion of the flow will have a spiral or helical flow direction.

The bearings 232a, 232b can have different configurations to enhance the performance of the pump 10. For example, the proximal bearing 232a can be longer along the longitudinal axis of the bearing housing 228 than the distal bearing 232b. A longer proximal bearing 232a is believed to better control runout of the shaft 204. Better runout control on the shaft 204 is believed to enhance the control of the position of the blades 212 relative to the housing 202. Less runout reduces excessive variation in the gap between the blades 212 and the housing 202, providing biocompatibility benefits such as reduced hemolysis.

In some embodiments, such as those in FIG. 5 where the bearings 232a, 232b are not friction fit or interference fit onto the shaft 204, the distal bearing 232b has a smaller inner diameter than the proximal bearing 232a. If the shaft 204 has a constant diameter, the smaller inner diameter should provide greater control of angular deflection of the shaft. Controlling angular deflection can enhance relative position control of the blades 212 and housing 202, providing blood handling benefits such as reduced hemolysis. A smaller clearance could also be provided by enlarging the diameter of the shaft 204 at the axial position of the distal bearing. In some embodiments, the larger inner diameter of the bearing 232b enables a larger volume of lubricant to flow proximally and a lesser volume to flow distally in the lumen 234.

The continuous introduction of lubricant maintains a constant, predictable and durable rotational bearing state between stationary component, e.g., the bearing housing 282, and a moving component, e.g., the shaft 204, a component of the bearings 232a, 232b, or both the shaft 204 and a component of the bearings 232a, 232b. Also, continuous lubricant inflow provides a means for removing heat generated by the relative motion between the shaft 204 and the bearings. Also, the infusant can create fluid pressure within the catheter assembly 100 that can push debris generated within or by the pump 10 out of the bearing housing 220. Enhancing the volume of infusant that flows along the path indicated by the arrow 304 enhances the likelihood that debris generated by or present in the pump will be removed from the proximal end rather than to be trapped inside the distal portion of the catheter assembly 100.

Another technique for controlling infusant flow in the lumen 234 is to locate the port 264 between the bearings 232a, 232b and closer to one of the bearing. For example, the ports 264 can be located adjacent to the proximal bearing 232a in one embodiment. This provides a shorter path of egress out of the narrow portion 240 of the bearing housing 228 in the proximal direction.

Other strategies for controlling the flow of infusant within the bearing housing 228 include modifying a surface within one or more of the bearings 232a, 232b. FIG. 8 shows a surface modification 233 provided in a bearing 232a to enhance proximally directed flow. The surface modification 233 comprises a plurality of axially oriented grooves 235 in one embodiment. In another embodiment, the surface modification 233 includes one or more spiral grooves. The spiral grooves can be formed with a groove entrance that is substantially parallel with a flow direction of infusant between the bearings 232a, 232b such that a reduction of velocity of the flow is minimized. In one embodiment, each spiral groove includes at least about 3 turns disposed on the inner surface of the bearing between the proximal and distal ends of the bearing. In another embodiment, each spiral groove has adjacent

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turns that are spaced apart by a minimum pitch of 0.125 inches (3.2 mm). In another embodiment, each spiral groove has an axial density of about 32 turns per inch (about 1.3 turns per mm). The grooves are formed in the surface 237 of the bearing 232a upon which the impeller shaft 204 is supported. The grooves 235 locally enlarge the clearance between the shaft 204 and the surface 237 so that a greater volume of infusant can flow distal-to-proximal across the bearing 232a. The surface modification 233 reduces back-pressure limiting the distal-to-proximal flow across the bearing 232a.

In other embodiments, it may be desirable to enhance distally directed flow. For example, the infusant may be provided with a fluid intended to be delivered to the patient. In such embodiments, the surface modification 233 can be provided on the distal bearing 232b. In certain embodiments, both proximal and distal bearings 232a, 232b are provided with flow enhancing modifications to enhance heat transfer or purging of the bearing assembly 220. In such embodiments, one of the bearings may have a greater degree of flow enhancement provided on the bearing surface.

The arrangement of the bearing assembly 220 can be a factor in selecting an appropriate infusant. Saline is a preferred infusant, but other sufficiently biocompatible infusants could be used. Other embodiments are configured such that little or no infusant flows out of the pump into the patient. For such embodiments, other infusant fluids can be used, such as glucose.

FIG. 7 illustrates further features of the catheter body 120. The catheter body 120 comprises an inner most portion 320 that defines the central lumen 286. The inner most portion 320 is disposed within, e.g., circumferentially surrounded by, the peripheral circumferential region 284. A continuous outer circumferential region 324 can be provided around the peripheral circumferential region 284 to fully enclose the lumens 282, discussed above. FIGS. 4A and 4B illustrate that a distal end of the inner most portion 320 is configured to be received and secured within a proximal portion of the lumen 234 within the bearing housing 228. FIG. 4B illustrates that a region of overlap can be provided between a distal portion of the inner most portion 320 and a proximal portion of the bearing housing 228. This construction provides a continuous lumen defined in part by the central lumen 286 of the catheter body 120 and in part by the lumen 234 of the bearing housing. In another arrangement, the bearing housing 228 and the catheter body 120 are joined by a coupler that enhances the sealing between infusant inflow through the lumens 282 and the channels 260 and the infusant outflow through the central lumen 286. As discussed further below, this continuous lumen provides a space for the rotation of the shaft 204 of the impeller assembly 116 and the drive shaft 148 of the torque coupling system.

The physical connection between the bearing housing 228 and the catheter body 120 can be achieved in any suitable manner. FIG. 3 illustrates that in one arrangement, a slideable connection is provided. In this arrangement, a rod 332 is provided between the bearing housing 228 and the catheter body 120. The rod 332 can have any suitable configuration, but may have a proximal end configured to be received in a recess or lumen formed in the catheter body 120 and a distal end 340 configured to couple with the bearing housing 228. FIG. 3 shows that the distal end 340 of the rod 332 can be configured to engage with a feature of the bearing housing 228 so that a limited range of sliding is permitted.

In one embodiment, the bearing housing 228 has an elongate channel 342 configured to receive a middle portion of the rod 332 and an enlarged depression 344 located at the distal end of the channel 342. The depression 344 has a width W that

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is sufficient to receive a wide distal end of the rod 332. The depression 344 can be configured to have an axial length along the housing 228 that can define a range of motion of the bearing housing 228 relative to the catheter body 120.

In one arrangement, the bearing housing 228 is positioned relative to the catheter body 120 and the rod 332 such that the distal portion of the rod 332 is located at the distal end of the depression 344. Thereafter, the catheter assembly 100 can be manipulated such that the bearing housing 228 moves distally relative to the catheter body 120 and the rod 332 such that the distal portion of the rod 332 is located at the proximal end of the depression 344. In the distal position, the impeller assembly 116 is located more distally than in the proximal position. As discussed further below, this enables a variety of techniques for unfurling the impeller blades 212 within the housing 202.

## B. Bearing Configurations

Any suitable bearing can be used in the catheter assembly 100. The provision of an infusant for hydrodynamic support enables a wide range of bearing materials to be used. If saline or other more corrosive infusant is used, the bearing must be carefully configured to not degrade within the expected duty cycle of the pump 10. Some polymeric materials are advantageously not degraded by isotonic saline, and are acceptable materials from this perspective. Under the fluid-dynamic conditions, a hydrodynamic bearing that is supported by a biocompatible infusant such as isotonic saline is preferred. It is believed that certain polymer bearings in combination with isotonic saline can support such conditions as 35,000-50,000 psi-ft/min for an appropriate duty cycle. Other aspects that can guide the choice of bearing configurations include minimizing thermal expansion, given the heat that could be generated in the heart pump 10, and minimizing moisture absorption.

Any suitable polymeric material may be used for the bearings 232a, 232b. The polymeric material can include a homopolymer, a copolymer, or a mixture of polymers. The polymeric material can include thermoplastic or thermoset polymers. Examples of polymers that can be used for bearings 232a, 232b include, but are not limited to, one or more of a polyketone, a polyether, a polyacetal, a polyamide-imide, a polyacetal, polyether ether ketone (PEEK), polytetrafluoroethylene (PTFE), and polyphenylene sulfide (PPS).

The polymeric material can also include (e.g., can be mixed, combined, and/or filled with) one or more additives such as a reinforcer and a lubricant. Specific additives include, but are not limited to, graphite, carbon fiber, glass fiber, and PTFE. Those of ordinary skill in the art may appreciate that the additives may be polymeric or non-polymeric. In some embodiments, the polymeric material used for bearings 232a and/or 232b can include PEEK, carbon fiber, PTFE, and graphite. In other embodiments, the polymeric material can include PPS and glass fiber. In yet other embodiments, the polymeric material can include a polyamide-imide polymer, carbon fiber, and graphite. The polymeric material can include any suitable amount of additive(s). For example, the polymeric material can include a total amount of additive(s) in the range of from about 1 wt % to about 50 wt %, based on the total weight of the polymeric material. In other embodiments, the polymeric material used for bearings 232a, 232b may not include any additives.

The polymeric material chosen for bearings 232a, 232b can have particular characteristics that advantageously affect the performance of the bearings. For example, in order to minimize thermal expansion caused by the heat generated in

the heart pump **10**, a preferred material would be subject to a minimum of dimensional change, and can have a coefficient of thermal expansion in the range of from about  $1.2 \times 10^{-5} \text{ } ^\circ \text{F}^{-1}$  to about  $25.2 \times 10^{-5} \text{ } ^\circ \text{F}^{-1}$ . In other embodiments, the polymer used for bearings **232a**, **232b** has a coefficient of friction in the range of from about 0.15 to about 0.3. In another example, in order to minimize or prevent water adsorption, the selected polymeric material can have a water adsorption in the range of from about 0.01% to about 0.4% over a 24 hour period. In yet another example, the polymeric material can be suitable for high pressure and velocity performance, and can have a limiting pressure-velocity (PV) in the range of from about 20,000 psi-ft/min to about 50,000 psi-ft/min.

The polymeric material used for bearings **232a**, **232b** may be commercially available. Examples of suitable, commercially-available polymeric materials include, but are not limited to, Ketron PEEK-HPV, Turcite A, Turcite X, Turcite TX, Rulon LR, Rulon J, Rulon 641, Rulon AR, Techtron HPV PPS, Ryton PPS, Torlon 4301, and Torlon 4501. In some embodiments, the polymeric material used for bearings **232a**, **232b** is Ketron PEEK-HPV.

Of course, other bearing configurations and/or materials would be suitable under other conditions, e.g., with less corrosive infusants or if a hydrostatic or non-hydraulic bearing is used.

### C. Torque Coupling Systems

A torque coupling system is provided to rotate the impeller **200** at a high rate to move blood from inside a heart chamber to a location within a patient's vasculature in amounts sufficient to sustain the patient or provide treatment to the patient. The torque coupling system couples the impeller **200** with the motor **136**, which may be disposed outside the patient. It is expected that the impeller **200** and the drive shaft **148** are to be rotated at 25,000-30,000 revolutions per minute for a period of seven to ten days. To provide reliable performance under these conditions, isotonic saline or other lubricant is provided between the drive shaft **148** and stationary components therearound.

FIGS. **11** and **4B** illustrate proximal and distal portions **400**, **404** of the drive shaft **148**. The proximal portion **400** is coupled with the drive assembly **146** such that rotation of the drive assembly **146** rotates the drive shaft **148**. The distal portion **404** of drive shaft **148** is coupled with the impeller shaft **204** such that rotation of the drive shaft **148** causes rotation of the impeller shaft **204**. The drive shaft **148** also includes an elongate body **408** that extends between the proximal and distal portions **400**, **404**. The elongate portion **408** comprises a lumen **412** extending therethrough.

The size of the elongate body **408** may be as small as possible to minimize the cross-sectional profile of the catheter assembly **100**. The cross-sectional profile of the catheter assembly **100** corresponds to the crossing profile of the catheter assembly, which limits where the system can be inserted into the vasculature. The lumen **412** is sized to permit a guidewire to be advanced therethrough in some embodiments. The use of a guidewire is optional, but may simplify insertion.

In one embodiment, the elongate body **408** comprises a multi-layer construction. In some embodiments, each layer can include at least one coil wire or a plurality of coil wires all wound in a same orientation. For example, a two-layer, counter-wound wire construction is particularly advantageous. A first layer (e.g., an inner layer) of the elongate body **408** is provided by a coiled wire of nickel-molybdenum-

chromium alloy, such as 35NLT or MP35N. In other embodiments, the wire material can be MP35N LT. In one embodiment, the wire has a 0.008 inch diameter and the coil has a 5 filar right-hand wound construction. The outer diameter of the first layer may be about 0.071 inch. A second layer (e.g., an outer layer) of the elongate body **408** can include the same material as the first layer, disposed on the outside of the first layer. The first and second layers can be wound in the same direction, or in opposite directions. For example, in some embodiments the first layer (e.g., an inner layer) can be left-hand wound and the second layer (e.g., an outer layer) can be right-hand wound, or vice versa. In other embodiments, both the first and second layers can be left-hand wound. In yet other embodiments, both the first and second layers can be right-hand wound. The wound coil wire construction can advantageously facilitate proximal and/or distal flow of infusant along the outer layer of the elongate body **408**. For example, the outer layer can be constructed such that the infusant travels along the coil and/or in the direction of the winding. Those skilled in the art may appreciate that, depending on the direction of rotation of the elongate body **408**, the infusant flow can advantageously be directed either proximally or distally. The second layer may be a 5 filar left-hand wound construction. In one embodiment, each layer is formed using a 0.008 inch diameter wire, in the above-noted coiled configuration. In other embodiments, the elongate body **408** can include three or more coil wire layers, wherein the layers are wound in alternating directions. In some embodiments, the outer diameter of the second layer can be between about 0.072 inch and about 0.074 inch, while in other embodiments the diameter can be much larger or smaller. In some aspects, for example, the outer diameter of the second layer can be about 0.073 inch. The inner diameter of the elongate body **408** can be at least about 0.039 inch in some implementations. In some embodiments, one or more ends of the elongate body **408** can be welded and square cut, for example, with a 0.1 inch maximum weld length on each end. The length of the elongate body **408** can vary, but in some embodiments, the length can be between about 47 inches and 48 inches, for example, about 47.5 inches.

Other materials and other constructions are possible. The elongate body **408** can be made of other non-ferrous metals or other corrosion resistant material or constructions with appropriate modulus. Other materials that could meet the corrosion requirements include stainless steel (e.g., **302**, **304**, or **316**). In certain embodiments, the elongate body **408** can have a structure that enables other materials to be used. For example varying at least one of coil layers, filars, wire diameter, and coil diameter may enable an otherwise less robust material to operate below the fatigue stress of that material.

In another embodiment, a four layer construction is provided. The four layers comprise three wire-wound layers, e.g., similar to the arrangement described above, but included a third wound layer on the outer surface of the second layer. A low friction layer can be disposed on the outside surface of the elongate body **408**. One material that could be used as a low-friction layer is PTFE, known commercially as TEFLON®. The low-friction layer should be configured to have sufficient wear resistance, such as by selection of the appropriate PTFE material, e.g. polyphenylene sulphone-filled PTFE, and/or by insuring appropriate infusant flow is maintained during the entire duration of use of the device in order to prevent undesirable local elevated temperature of the PTFE material.

The drive shaft **148** operates within the multilumen catheter body **120**. Because the drive shaft **148** is rotated at a very high rate when in use within the multilumen catheter body

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**120**, the configuration of the surface forming the central lumen **286** is important. In some embodiments, this inner surface has high lubricity and high wear resistance. One material that can be used for the inner surface of the catheter body **120** is high density polyethylene (HDPE), which provides sufficient lubricity and wear resistance. In one embodiment, the entire multilumen catheter body **120** is formed of HDPE. PTFE provides good lubricity and could be used if made sufficiently wear resistant. One way to increase the wear resistance of PTFE is to impregnate it with polyphenylene sulphone (PPSO<sub>2</sub>), another is to gamma irradiate the material. One way to increase the lubricity of Polyimide materials is to impregnate it with Graphite, another is to impregnate it with Graphite and PTFE.

FIG. 4B shows a clearance **412** between the elongate body **408** of the drive shaft **148** and the inner surface of the multilumen catheter body **120**. The clearance **412** may be about 0.005 inch. Along a diameter between opposite sides of the inner surface of the central lumen **286** and outer surface of the elongate body **408** includes about 0.010 inch of space or diametric clearance. A larger minimum clearance may be desirable if the crossing profile can be enlarged or if other structures of the catheter assembly **100** can be made thinner or eliminated to allow more room between the elongate body **408** and the central lumen **286**.

FIGS. 11 and 12 show further details of the drive assembly **146**, which is disposed at the proximal end **104** of the catheter assembly **100**. The drive assembly **146** includes a drive housing **450** having a recess or cavity **454** disposed therein. The cavity **454** is configured for mounting a rotor support shaft **458** for rotation therein. The support shaft **458** has a proximal end and a distal end and a plurality of components mounted thereon. The distal end of the support shaft **458** has a recess **462** formed therein to receive a proximal end of the drive shaft **148**. The support shaft **458** may also have a lumen **466** disposed therein for slideably receiving a guidewire.

A rotor **470** is mounted on an outer surface of the support shaft **458** between sleeve bearings **474a**, **474b**, as shown in FIG. 12. The rotor **470** can take any suitable form, but in one embodiment includes an elongate magnet **476** disposed between proximal and distal flywheels **478a**, **478b**.

The proximal end of the support shaft **458** has a tapered port **480** for receiving the guidewire. The proximal end can be configured for engaging the motor **136** in some embodiments. In other embodiments, a magnetic field is induced by the motor **136** in a manner that creates torque and rotation of the shaft **458**.

An infusant outflow path **482** is provided within the drive assembly **146**. The outflow path **482** is provided between an outer surface of the support shaft **458** and an inner surface **486** of the distal bearing. The flow path **482** continues from the distal bearing **474b** radially outwardly along thrust surfaces **490a**. The flow path continues proximally between the outer surface of the rotor **470** and the inner surface defining the cavity **454**. The flow path **482** continues radially inwardly along the thrust surface **490a** toward the support shaft **458**. The flow path **482** continues proximally between the support shaft **458** and the proximal bearing **474a**. Proximal of the bearing **474a**, the flow of infusant exits the catheter assembly **100** through an outflow port **144** through which it can be directed to the waste container **46** or discarded. The flow path is shown in more detail in FIGS. 1, 12, 12A, and 12B.

### III. Structures that Facilitate Deployment and Retrieval

The catheter assembly **100** can include one or more features that facilitate the deployment and/or retrieval of one or

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more components of the distal end **108** of the heart catheter assembly **100** (e.g., the impeller assembly **116** or a portion thereof).

#### A. Optionally-Expandable Diffuser

As shown in FIGS. 13A and 13B, the pump can include a diffuser **502a**, **502b**. As illustrated in FIG. 13A, in some embodiments the diffuser **502a** is connected to the impeller hub **208**. For example, the diffuser **502a** can be integral, or form a unitary structure, with the impeller hub **208**. In another example, the proximal end of the impeller hub **208** can include the diffuser **502a**. As illustrated in FIG. 13B, in other embodiments, the diffuser **502b** is separate from (e.g., not connected to) the impeller hub **208**.

The diffuser **502a**, **502b** can be disposed between the distal end of the elongate body of the catheter body and the impeller. The diffuser **502a**, **502b** can be configured to be positioned within the housing **202** and adjacent to the proximal opening of the housing. In some embodiments, the diffuser **502a**, **502b** can be axially aligned with the proximal opening of the housing **202**. Advantageously, this configuration can maximize the flow directing capabilities of the diffuser **502a**, **502b**, as discussed further herein. The diffuser **502a**, **502b** can be located adjacent the proximal end of the hub **208**. The diffuser **502a**, **502b** can include a proximal end **504a**, **504b** and a distal end **505a**, **505b**. The proximal end **504a**, **504b** of the diffuser **502a**, **502b** can be positioned adjacent the distal end of the bearing housing **228** (e.g., over a bearing **516** and/or a front thrust washer **518**). As shown in FIG. 13A, the proximal end **504a** can be separated from the bearing **516** by a gap **522**. The gap **522** can have an axial length generally equal to the length of the bearing **516**. The gap **522** can also be generally cylindrical with a longitudinal axis that is aligned with the longitudinal axis of the impeller shaft **204**. The distal end **505a**, **505b** can be located adjacent the proximal end of the impeller hub **208**. The diffuser **502a**, **502b** can include a flow directing surface. For example, an outer surface **513** of the diffuser **502a**, **502b** can form a curved line from the proximal end **504a**, **504b** to the distal end **505a**, **505b**, as illustrated in FIGS. 13A-B. As viewed from the proximal or distal end, the diffuser **502a**, **502b** can have a generally circular cross sectional shape. As shown in FIGS. 13A and 13B, the diameter of the diffuser **502a**, **502b** can be greatest in the mid section and can taper to a smaller diameter in the distal and/or proximal directions. The diffuser **502a**, **502b** can have a maximum diameter that is generally greater than the diameter of the hub **208** and/or the bearing housing **228**. The diameter of the proximal end **504a**, **504b** can be generally equal to the diameter of the bearing housing **228**. The diameter of the distal end **505a**, **505b** can be generally equal to the diameter of the hub **208**. The diffuser **502a**, **502b** may be referred to herein as a bulge, and in various embodiments can have a radially enlarged portion disposed downstream of the impeller.

Advantageously, the relatively large diameter and/or the curved outer surface can assist in directing (e.g., diffusing) fluid flow out of the housing **202**. The geometry of the diffuser **502a**, **502b** (e.g., the radius of curvature of the outer surface) can be optimized to control desired fluid properties such as boundary layer flow, laminar flow, and pressure gradients and to reduce outlet flow losses.

The diffuser **502a**, **502b** can include a wall **511**. The wall **511** can include an inner surface **512** and the outer surface **513**, described above. The wall **511** can have a thickness extending from the inner surface **512** to the outer surface **513**. In some embodiments, the wall **511** can have a generally uniform thickness along the axial length of the diffuser **502a**,



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**502b**. One advantage of a generally uniform wall thickness is that the diffuser **502b** can be more easily expanded and/or collapsed, as described herein. In other embodiments, the wall **511** can have a variable thickness along the axial length of the diffuser **502a**, **502b**. For example, as illustrated in FIG. **13A**, the thickness of the wall **511** can increase in the distal direction. One advantage of a variable thickness wall is that it can have variable structural strength. For example, a wall having a thickness that increases distally can advantageously have greater strength in areas that are most exposed to oncoming blood flow.

The inner surface **512** can define a chamber **506** through which the impeller shaft **204** can pass. As shown in FIG. **13A**, the diffuser **502a** can form part of the proximal end of the hub **208** of the impeller **200** (e.g., the hub **208** can be connected to the diffuser **502a**). Thus, the diffuser **502a** can rotate with the rotating hub **208**. The diffuser **502a** can also include a proximal cavity outlet **508**. As shown in FIG. **13B**, the diffuser **502b** can be a component separate from the impeller **200**. In this embodiment, the diffuser **502b** can be stationary when the hub **208** is rotating. The diffuser **502b** can also include a distal cavity outlet **510**.

There can be many advantages to including a diffuser **502a** that is connected to the impeller hub **208**. For example, the unitary construction can be easier to manufacture and/or assemble. As described herein, the distal end of the diffuser **502a** can be relatively thick and strong (e.g., stiff). In addition, it can be advantageous for the infusant to exit the catheter assembly **100** at the proximal outlet **508**, which is generally at the downstream end of the diffuser **502a**.

There can also be advantages to including a diffuser **502b** that is a structure separate from and not directly attached to the impeller hub **208**. In some embodiments, the diffuser **502b** can be made from a material that is different from the material used to make impeller hub **208**. For example, the diffuser **502b** can be made from a material that is relatively more flexible (softer) than the material of the impeller hub **208**. In other embodiments, the wall **511** of diffuser **502b** can have a generally uniform thickness. These features of diffuser **502b** can facilitate the expansion and/or contraction of the diffuser **502b**, described further herein.

As shown in FIGS. **13A** and **13B**, the diffuser **502a**, **502b** can be generally hollow, as defined by the chamber **506**. The diffuser **502a**, **502b** can be sufficiently hollow and can be made of a relatively flexible material (e.g., a polymer or elastomer) to be expandable and/or collapsible. For example, the maximum diameter of the diffuser **502a**, **502b** can expand from a first diameter to a second diameter. Advantageously, the collapsible diffuser **502a**, **502b** can have a deployed, expanded configuration, and a retracted, collapsed configuration. In the deployed, expanded configuration, the diffuser **502a**, **502b** can have a maximum diameter (e.g., as measured at the mid-section or bulge) that is generally greater than the diameter of the hub **208** and/or the bearing housing **228**. In the retracted, collapsed configuration, the diffuser **502a**, **502b** can have a reduced diameter. For example, in the retracted, collapsed configuration, the diffuser **502a**, **502b** can have a maximum diameter that is generally less than or equal to the diameter of the hub **208** and/or the bearing housing **228**. Although described as having a diameter, those skilled in the art may appreciate that while retracted and/or collapsed, the diffuser **502a**, **502b** may not have a generally circular cross section. A collapsible diffuser can be advantageous compared to a non-collapsible diffuser because a collapsible diffuser can allow the overall structure to maintain a low profile for the purpose of retracting back into a sheath and for insertion into and/or removal from a patient.

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In some embodiments, the relatively flexible material itself may not be significantly expandable (e.g., stretchable and/or elastic). Rather, the terms “expandable” and “collapsible” can refer to the overall expansion and/or collapse of the chamber **506** of the diffuser **502a**, **502b**. In other embodiments, the relatively flexible material itself may be significantly expandable (e.g., balloon-like).

The chamber **506** can be configured (e.g., sized) to allow fluid (e.g., infusant) flow through the diffuser **502a**, **502b**. The diffuser **502a**, **502b** can be configured for fluid communication with a fluid, such as an infusant, that passes through the bearing assembly **220**. The bearing assembly **220** illustrated in FIGS. **13A** and **13B** can have many, if not all, of the same features as described with respect to the bearing assembly **220** illustrated in FIG. **5**. As shown in FIGS. **13A** and **13B**, the infusant can follow an infusant path **514a**, **514b** out of the bearing assembly **220** and into the diffuser **502a**, **502b** via a passage or cavity **520** between the bearing **516** and the washer **518**. For at least a portion of the infusant path **514a**, **514b**, the infusant can travel distally. In some embodiments, at least a portion of the infusant path **514a**, **514b** can be non-helical (e.g., generally linear). In other embodiments, at least a portion of the infusant path **514a**, **514b** can be generally helical. The helical shape of the infusant path **514a**, **514b** can be caused at least in part by rotation of one or more components of the impeller assembly **116** (e.g., the impeller shaft **204** and/or impeller hub **208**).

As illustrated in FIG. **13A**, the infusant path **514a** can extend from the proximal end **504a** to the distal end **505a** and can return back to the proximal end **504a** to exit the proximal outlet **508** via the gap **522**. The portion of the infusant path **514a** that extends from the proximal end **504a** to the distal end **505a** is helical (e.g., can encircle the impeller shaft **204** one or more times along the axial length of the path). The return portion of the infusant path **514a** can be non-helical (e.g., generally linear). The return portion of the infusant path **514a** can be non-helical at least in part because the return portion can follow the curved interior surface **512** of the diffuser wall **511**. In use, the infusant can exit the bearing assembly **220** at the cavity **520** to enter the chamber **506**. At least a portion of the infusant can then follow infusant path **514a** to travel helically around the impeller shaft **204** in the distal direction until the distal end **505a** is reached. The infusant then changes direction and turn around to flow proximally along the non-helical return portion of the infusant path **514a** and through the gap **522** to exit the pump via the proximal cavity outlet **508**. Although shown as a single distal-to-proximal line, in some embodiments, exit flow can be induced along and generally following the shape of the inner surface **512** to the proximal cavity outlet **508**. In use, as the infusant passes through the gap **522**, the infusant can act as a hydrodynamic bearing (e.g., in addition to the hydrodynamic bearing that may be present between the impeller shaft and the bearing housing as described herein). This hydrodynamic bearing can generally be in the shape of a cylinder that extends axially, as defined by the gap **522**. Advantageously, this hydrodynamic bearing can reduce friction between the diffuser **502a** and the bearing housing **228**.

As illustrated in FIG. **13B**, the infusant path **514b** can extend from the proximal end **504b** to the distal end **505b**. As illustrated in FIG. **13B**, the infusant path **514b** is helical (e.g., can encircle the impeller shaft **204** one or more times along the axial length of the path). In use, as shown in FIG. **13B**, generally all of the infusant flows proximally to distally within a distal portion of the bearing assembly **220** and exits the bearing assembly at the cavity **520** to enter the chamber **506**. In various embodiments, a portion of the infusant flows



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proximally within a proximal portion of the bearing assembly 220 through a space between the drive shaft 148 and the catheter body 120. This return flow is discussed above, e.g., in connection with arrow 304 in FIG. 8. At least a portion of the infusant then follows the infusant path 514b to travel helically around the impeller shaft 204 in the distal direction and out through the distal cavity outlet 510. As illustrated in FIG. 13B, the distal cavity outlet 510 defines a gap between the distal end 505b of diffuser 502b and the proximal end of impeller hub 208. In use, as the infusant passes through the distal cavity outlet 510, the infusant can act as a hydrodynamic bearing. This hydrodynamic bearing can generally be in the shape of a cylinder having a length extending axially along the length of the gap and a radius corresponding to the cross sectional radius of the gap. Advantageously, this layer of infusant between the diffuser and the impeller hub can reduce friction between the diffuser 502b and the impeller hub 208 when the pump is in operation.

As described herein, the diffuser 502a, 502b can be expandable. In some embodiments, one or more forces exerted by the infusant can be used to expand the diffuser 502a, 502b. The flow rate of the infusant can be sufficient to establish an area of positive pressure within the diffuser 502a, 502b, thereby allowing at least a portion of the infusant to exit adjacent to a distal end of the device. In some embodiments, the static pressure of the infusant entering the chamber 506 can cause the diffuser 502a, 502b to expand. In any of these embodiments, an inflated diffuser 502a, 502b can be deflated by interrupting and/or discontinuing the flow of infusant into the diffuser 502a, 502b and by allowing the infusant to exit the diffuser via the proximal outlet 508 or the distal outlet 510. In some embodiments, the wall is elastic but the pliability is relatively low such that upon removal of the infusant flow a transition from expanded to low profile is rapid. The diffuser 502a, 502b self-collapses displacing the infusant out of the chamber 506 through one or more small apertures. In addition to promoting quick deflation, the relatively low pliability will provide a uniform diffuser profile, e.g., will not be deformed or deflected by any varying pressure or flow rate of the blood from the impeller 200. A lower infusant pressure configuration can also be provided by increasing the pliability of the structure forming the diffuser 502a, 502b. The structure can be of enhanced pliability by material selection or constructions (e.g., by being thinner or adopting other balloon-like features).

In other embodiments, the centrifugal force exerted by the infusant as it travels along the helical path 514a, 514b can be used to expand the diffuser 502a, 502b. As illustrated in FIG. 13A, the diffuser 502a can be connected to the impeller assembly 116. In these embodiments, the diffuser 502a and the impeller assembly 116 can be rotated. In use, when the impeller assembly 116 and the diffuser 502a are rotated, the infusant can also rotate due to, e.g., shear forces generated from the fluid contact with the rotating diffuser 502a and/or the rotating impeller shaft 204. The rotating infusant can exert a pressure on the inner surface 512 to thereby expand the diffuser 502a from the collapsed configuration to the expanded configuration. Thus, in some embodiments, the diffuser 502a can be centrifugally expanded. In yet other embodiments, the diffuser 502a can be expanded using a combination of static and centrifugal forces.

As illustrated in FIG. 13B, the diffuser 502b may not be rotatable. In these embodiments, when the impeller shaft 204 is rotated, the infusant can also rotate due to, e.g., shear forces generated from the fluid contact with the rotating impeller shaft 204. As described herein, the rotating infusant can exert a pressure on the inner surface 512 to thereby expand the

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diffuser 502b from the collapsed configuration to the expanded configuration. Thus, in some embodiments, the diffuser 502b can be centrifugally expanded. In yet other embodiments, the diffuser 502b can be expanded using a combination of static and centrifugal forces.

Infusant exiting the diffuser 502a, 502b can be continuously replenished with additional infusant via the flow path 514. If the impeller shaft 204 stops rotating, the pressure generated from rotation can decrease to match the pressure acting on the outside of the diffuser 502a, 502b, thereby allowing the diffuser 502a, 502b to collapse.

In yet other embodiments, the diffuser 502a, 502b can be expanded and/or inflated by a combination of static and centrifugal forces. For example, the diffuser 502a, 502b can be expanded and/or inflated by a combination of the static force of the infusant as it enters the chamber 506 and the centrifugal force of the infusant as it travels along the helical path 514.

#### B. Relatively Axially-Moveable Impeller Housing

As illustrated in FIG. 14B, when the impeller and the diffuser 502 are in the proximal position, at least a portion of the impeller (e.g., the blades 212 and/or the hub) and/or the diffuser 502 may be relatively positioned in a portion of the housing 202 having minimal or no coating, such as an outlet 802 of the housing 202 (e.g., the outlet through which blood is pumped). In some embodiments, the housing 202 can be moved axially relative to the impeller and/or the diffuser 502. In some embodiments, the housing 202 is moved axially over the impeller and the impeller is stationary. Those skilled in the art may appreciate that in some embodiments, the housing 202 may not be configured to move axially relative to the impeller and/or the diffuser 502 (e.g., housing 202 is fixed or stationary relative to impeller and/or the diffuser 502). For example, the housing 202 and the diffuser 502 can be spaced apart by a relatively constant axial distance in all operational states, or at least in a collapsed and an expanded state.

As illustrated in FIGS. 14A and 14B and as described herein, the rod 332 provided between the catheter body 120 and the bearing housing 228 enables a slideable engagement between the catheter body 120 and the bearing housing 228. The distal end of the catheter body 120 can be connected to the proximal portion 268 of the impeller housing 202. The catheter body 120 can translate distally from a proximal position to a distal position, and vice versa, by the application of an axial force described further herein. As described herein, for example with respect to FIGS. 4A-4B, the catheter body 120 can be coupled to the proximal portion 268 of the impeller housing 202. For example, the proximal portion 268 of the impeller housing 202 can be fitted over the distal end of the catheter body 120.

In the proximal position, illustrated in FIG. 14A, the axial position of the outlet 802 can be proximal of the axial position of the proximal-most blade 212. In the distal position, illustrated in FIG. 14B, the axial position of the outlet 802 can generally correspond to the axial position of the proximal-most blade 212. Advantageously, the rod 332 and the enlarged depression 344 can control the axial distance over which the impeller housing 202 is capable of sliding. The rod 332 can also advantageously prevent the bearing housing 228 from rotating with the impeller shaft 204.

Those skilled in the art may appreciate that the axial movement of the catheter body 120 and the impeller housing 202 relative to the impeller and/or the diffuser 502 can have the same relative effect as axially moving the impeller and/or the diffuser 502 relative to the catheter body 120 or the impeller housing 202, even if the impeller and/or the diffuser are not

actually moved axially. Accordingly, in some embodiments the catheter body **120** in the proximal position can be referred to as the deployed position of the impeller and/or the diffuser **502**. The catheter body **120** in the distal position can be referred to as the retracted position of the impeller and/or the diffuser **502**.

The ability of the impeller and/or the diffuser **502** to be retracted and deployed relative to the impeller housing can have many advantages. For example, axial movement of the impeller housing relative to the impeller and/or the diffuser can reduce the profile of the pump to ease insertion and retrieval. In some embodiments, in the retracted position, the impeller hub **208**, blades **212**, and/or diffuser **502** can be positioned at the same axial location as a portion of the housing **202** that does not have a covering (e.g., the outlet **802**). Accordingly, the cross-sectional area of the catheter assembly **100** measured at the axial position of the diffuser **502** in the retracted position, for example, is comparatively smaller than when it is in the deployed position. The smaller cross sectional area can be advantageous for minimizing trauma to a user during insertion into and/or retrieval from the body.

In other embodiments, the retracted position of the impeller and/or the diffuser can be distal of the deployed position of the impeller and/or the diffuser. In some embodiments, the impeller housing can have a rigidity that varies axially. For example, the impeller housing can have a proximal portion that is more rigid (e.g., less flexible) than a distal portion. In these embodiments, the impeller and/or the diffuser can reside in the proximal, rigid portion while in the deployed position. The impeller and/or the diffuser can reside in the distal, flexible portion while in the retracted position. Advantageously, when the impeller and/or the diffuser reside in the flexible portion of the impeller housing, this portion of the pump may be collapsed to a lower profile than would otherwise be achievable if the impeller and/or the diffuser remained in the rigid portion of the impeller housing.

As described herein, the catheter body can be coupled to the impeller housing. The retraction and deployment (e.g., movement between proximal and distal positions) of the impeller housing can be controlled by manipulation of a proximal end of the catheter assembly that results in an application of axial force to the catheter body. For example, the impeller housing can be moved axially by the rotational force applied by a nut disposed at the proximal end of the catheter assembly. A section of the proximal end of the catheter assembly is illustrated in FIGS. **15A** and **15B**.

In some embodiments, axial force is applied to the catheter body via an impeller deployment assembly **800**. The impeller deployment assembly includes a nut **804** that is engaged with a portion of the catheter assembly, such as a flow diverter **806**. As described herein, the flow diverter **806** can be a part of the infusion inflow assembly **150**, illustrated in FIG. **1**. The distal end of the flow diverter **806** can be connected to a proximal portion of the catheter body. In some embodiments, the nut **804** can be engaged with a pin **808**. The pin **808** can penetrate through the wall of the drive housing **450** and can be coupled with or fixedly attached to the flow diverter **806**. The nut **804** can be disposed over at least a portion of the drive housing **450** and/or the flow diverter **806**. The nut **804** can include an internal engagement structure that is configured to engage the flow diverter **806** (e.g., via the pin **808**). In some embodiments, the internal engagement structure can include internal threading. In other embodiments, the internal engagement structure can include a cam track **812** having first and second ends (e.g., a proximal end and a distal end), as illustrated in FIG. **15C**. In these embodiments, the pin **808** can be config-

ured to travel along the cam track **812**. The internal engagement structure can be generally helical. The drive housing **450** can also include a longitudinal channel **810** along which the pin **808** can travel.

As illustrated in FIGS. **15A** and **15B**, the drive housing **450** can contain the support shaft **458** and the drive shaft **148**. The drive housing **450** can also capture the nut **804**. For example, a retention structure can be formed in the outside surface of the housing **450** to prevent the nut **804** from slipping proximally or distally relative to the housing **450**. One embodiment of a retention structure is illustrated below in connection with the deployment device of FIGS. **15D-F** but can be included with the deployment device **800** as well. The pin **808** can penetrate the wall of the drive housing **450** and permit axial translation of the flow diverter **806** by acting as a cam. In some embodiments, the support shaft **458** and the thread advance nut **804** may be rotatable but not translatable relative to the drive housing **450**.

In use, a rotational force can be applied to the nut **804**. This application of rotational force can be converted into an axial force that is applied to the flow diverter **806** and the catheter body. As described herein, the pin **808** can be fixedly attached to the flow diverter **806** at one end and have a second end disposed within the inner surface of the nut **804** along the cam track thereof. The rotation of the nut **804** in a first direction (e.g., clockwise or counter-clockwise) can cause the pin **808** to translate from a proximal position (e.g., proximal end) to a distal position (e.g., distal end) in the longitudinal channel **810**. Accordingly, the flow diverter **806**, the catheter body, and the impeller housing can also translate from a proximal position to a distal position. As described herein, the distal translation of the catheter body and the impeller housing can improve the ease of the retraction of the impeller hub and the blades into the impeller housing. In embodiments where the outlet **802** is generally free of a polymeric coating, relative movement of at least a portion of the impeller and/or the diffuser proximally into the outlet **802** or distally into a more flexible region of the impeller housing (i.e., mid section of the housing where there is less strut material) can advantageously reduce the profile of the pump upon collapsing into the sheath. In addition, axial adjustment of the impeller housing relative to the impeller can advantageously promote more efficient flow dynamics. In some embodiments, the impeller is positioned closer to the outlet **802** than the middle portion of the housing in order to improve flow dynamics.

A rotational force applied to the nut **804** in a second direction (e.g., counter-clockwise or clockwise) can cause the pin **808** to translate from the distal position to the proximal position. Accordingly, the flow diverter **806**, the catheter body **120**, and the impeller housing **202** can also translate from a distal position to a proximal position. As described herein, the proximal translation of the catheter body **120** and the impeller housing **202** can effectively result in the deployment of the impeller hub **208** and the blades **212**.

FIGS. **15D-F** illustrate another embodiment of a deployment device **850** that can be used to manipulate or deploy a distal structure of the catheter assembly and/or the impeller housing. As with the deployment device **800**, the deployment device **850** can be used to actuate the impeller **200** between retracted and deployed configurations.

As discussed above, the catheter assembly can include a flow diverter **852** that is part of the infusion system. The flow diverter **852** may be coupled with a proximal portion **122** of the catheter body **120**. In one embodiment, the proximal end of the proximal portion **122** is inserted into a recess **854** formed at a distal **852a** end of the flow diverter **852**. The connection between the proximal portion **122** of the catheter

body **120** the flow diverter **852** can be further made secure by a strain relief **856** disposed at the junction and extending distally thereof. The strain relief **856** overlaps a proximal length of the proximal portion **122** and absorbs movements of the portions of the catheter assembly to isolate the connection between the flow diverter **852** and the catheter body. A cap **860** can be used to securely couple strain relief **856** to the flow diverter **852**. A proximal portion **862** of the flow diverter **852** is received within a recess **864** of the housing **450**. A seal device **866**, such as an O-ring, may be provided between the proximal portion **862** of the flow diverter **852** and inside surface of the recess **864** to prevent infusion from exiting the housing **450** in an undesirable manner.

The flow diverter **852** also includes a lumen **868** that extends from a proximal end **852b** to the distal end **852a** thereof. The lumen **868** is configured to permit a proximal portion of the drive shaft **148** to reside therein. In some embodiments, flow diverter **852** is configured to cause some infusant to flow proximally in the lumen **868** between the drive shaft **148** and the inner surface of the flow diverter **852** that forms the lumen **868** to lubricate and cool the drive shaft. The flow diverter **852** can be configured to cause most or substantially all of the infusant entering the diverter through the lumen in the catheter body **154** to flow distally between the catheter body **120** and the drive shaft **148**. In one arrangement, the lumen **868** is enlarged from a location proximal of where the catheter body **154** couples with the flow diverter **852** toward the distal end **852a** of the flow diverter. This enlargement creates a path of least resistance toward the distal direction to divert the flow distally. In one embodiment, the lumen **868** is further enlarged at a location between where the catheter body **154** couples with the flow diverter **852** and the recess **854** such that a substantially continuous lumen can be formed to keep flow resistance at the junction between the flow diverter **852** and the proximal portion **122** of the catheter body **120** to a minimum.

The deployment device **850** includes a guide track **872** on a proximal portion **862** of the flow diverter **852**, a guide member **874**, and an actuator **876**. The guide track **872** can comprise an axially oriented slot or recess formed in the outside surface of the proximal portion **862**. The guide track **872** may be configured to slidably receive a guide member **874** such that relative movement can be provided between the guide track **872** and a guide member **874**. A portion of the guide member **874** may extend through sidewall of the drive housing **450** such that the axial position of the guide member **874** can be fixed and relative movement is provided by movement of the flow diverter **852** relative to the guide member. In one embodiment the guide member **874** is a pin that has one end received in a small hole in the drive housing **450** and the other end disposed in the guide track **872**.

The actuator **876** is configured to translate rotational motion thereof into axial motion of the flow diverter **852**. For example, the actuator **876** can comprise a nut that includes internal threads that are engaged with external threads on the outside surface of the flow diverter **852**. In various embodiments, a proximal portion of the actuator **876** is anchored to the drive housing **450** to prevent the actuator **876** from moving axially along the drive housing. In one embodiment a retention structure **882** is provided between the actuator **876** and the drive housing **450**. One embodiment of the retention structure **882** is illustrated in detail B of FIG. **15D**. In particular, the retention structure **882** includes an inwardly protruding member **884** that is received in an annular recess formed in the outside surface of the drive housing **450**. The protruding member **890** can include an inwardly protruding ring

having a diameter that is less than the diameter of the actuator **876** distally and proximally of the protruding member **884**.

FIGS. **15E-F** illustrate operation of the deployment device. FIG. **15E** corresponds to an expanded configuration of the catheter assembly **100**. In this position, the pin **874** is positioned at the distal end of the guide track **872** and the flow diverter **852** is in a proximal position. Because the flow diverter **852**, the catheter body **120**, and the impeller housing are coupled together so that they move in unison, the catheter body **120** and the impeller housing are also positioned in a relatively proximal position. Relative axial movement is permitted between the impeller and the catheter body, as well as between the diffuser and the catheter body. Also, because the catheter body **120**, the flow diverter **852**, and the impeller housing move in unison, relative axial movement is permitted between the impeller (and/or diffuser) and the impeller housing. As a result, the impeller will be in a more distal position relative to the impeller housing when the catheter assembly **100** is in the configuration of FIG. **15E**. The more distal position moves the impeller into the largest volume portion of the impeller housing enabling the impeller to expand.

FIG. **15F** corresponds to a collapsed configuration of the catheter assembly **100**. In this position, the pin **874** is positioned at the proximal end of the guide track **872** and the flow diverter **852** is in a distal position. This causes the impeller to be in a more proximal position relative to the housing when the catheter assembly is in the configuration of FIG. **15F**. This more proximal position moves the impeller into engagement with the inside surface of the housing tending to collapse the impeller.

To move from the expanded configuration of FIG. **15E** to the collapsed configuration of FIG. **15F**, the actuator **876** is rotated in a manner that causes the threads to act upon each other which creates axial movement of the catheter body **120** and the impeller housing **202**.

#### C. Impellers Having Self-Sealing Impeller Tips and Lumens With Valves

In some embodiments, the tip **602** of impeller hub **208** can be self-sealable or resealable (e.g., configured to automatically effectively form a seal to substantially stop the flow of a fluid in the absence of direct action by a user or operator to form the seal), as illustrated in FIGS. **16A-C**. As illustrated in FIGS. **16B-C**, the tip **602** of impeller hub **208** can include a resealable member having a resealable path therethrough.

As shown in FIG. **16A**, the impeller tip **602** can be made of an elastomeric material (e.g., a silicone or polyisoprene polymer). As shown in FIG. **16A**, the tip **602** can include a resealable path **604** that extends along the length of the tip. The resealable path **604** can extend from the outer surface at the distal end of tip **602** to the impeller shaft, which can be hollow. The hollow shaft extension **606** is shown in FIGS. **16A** and **16B** connected by the resealable path **604** to the tip **602** and is connected at its proximal end to the impeller shaft **204**. Thus, the resealable path **604** can extend from the impeller shaft **204** to the outer surface of the tip **602**. The resealable path **604** can be configured for guidewire passage. The resealable path **604** can generally pass through the center of rotation of the impeller tip **602**.

The resealable path **604** can be created using a very small diameter, e.g., a 32 gauge (0.00925 inch or 0.235 mm) wire or pin. In some embodiments, the resealable path **604** can be created without coring the impeller tip **602** (e.g., without punching out or otherwise removing a cylinder of material). The resealable path **604** can be self-sealable. For example, the resealable path **604** can close or seal automatically, without

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the use of additional tools or implements. The resealable path **604** can be self-sealable due to the elastomeric properties of the material used for impeller tip **602** (e.g., a silicone or polyisoprene polymer) and/or the diameter of the resealable path **604**. In some embodiments, circumferential and radial forces of the tip material and/or external pressure forces (illustrated with arrows at **612**) exerted while the catheter assembly **100** is implanted can also contribute to sealing the resealable path **604**.

In some embodiments, the tip **602** or resealable member **622**, **624** can be made of the same material as the rest of the impeller system (e.g., hub, blades, shaft, and/or shaft extension). In other embodiments, the tip **602** or resealable member **622**, **624** can be made from a different material than the rest of the impeller system (e.g., hub, blades, shaft, and/or shaft extension). For example, the tip **602** or resealable member **622**, **624** can be made of a material that is more elastomeric (e.g., has greater elasticity) than the material from which the impeller shaft **204** and/or shaft extension **606** are formed. In another example, the tip **602** or resealable member **622**, **624** can be made from a polyisoprene polymer and at least a portion of the impeller shaft **204** (e.g., the distal end) and/or shaft extension **606** are formed from an acrylonitrile butadiene styrene (ABS) polymer or a polycarbonate polymer.

In some embodiments where the impeller tip **602** comprises a resealable member **622** that is made separately from the rest of the impeller system, the resealable member **622** can include one or more proximally-extending tabs **616**. The one or more tabs **616** can be disposed about the proximal end of resealable member **622**. In some embodiments, the resealable member **622** can include one generally cylindrical tab **616** that is disposed about the proximal end of the resealable member **622**. The one or more tabs **616** can be configured to mate with (e.g., can engage and/or be disposed within) one or more of the corresponding recesses **618** disposed on the distal end of a portion of the impeller assembly **116** (e.g., the hub **208**, shaft **204**, and/or shaft extension **606**). As illustrated in FIG. **16B**, the recess **618** can be bounded by the surfaces of the hub **208** and the shaft extension **606**. The one or more recesses **618** can be disposed about the distal end of impeller assembly **116**. In some embodiments, the distal end of the impeller assembly **116** can include one recess **618**. For example, the recess **618** can be a generally cylindrical channel surrounding at least a portion of the shaft extension **606**.

Engagement of the resealable member **622** with the distal end of the impeller assembly **116** as illustrated in FIG. **16B** can have many advantages. For example, an interface **620** between the resealable member **622** and the distal end of the impeller assembly **116** can be non-planar. Accordingly, a non-planar interface **620** can have a greater surface area than an otherwise similar interface that is planar. The increased surface area can advantageously increase the connection strength between the resealable member **622** and the distal end of the impeller assembly **116**. In one embodiment, the interface **620** can be much longer than the radial distance from the lumen **610** to the outer surface of the hub **208**. For example, the interface **620** can be at least about twice as long as this radial distance.

As illustrated in FIG. **16B**, resealable member **622** can include a valve **608** that extends proximally into an axial lumen **610**. One valve structure that can be used is a duck bill valve. The lumen **610** can pass through one or more components of the distal end of the impeller assembly **116**, such as the impeller shaft **204**, the impeller shaft extension **606**, and/or the hub **208**. The lumen **610** can have a diameter that is greater than the diameter of the resealable path **604**. The

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lumen **610** may also not be self-sealing. The valve **608** can be tapered or otherwise have a reduced cross section compared to the lumen **610**. As a result, the impeller tip can also include one or more corners **614** where the lumen **610** extends distally to overlap with the valve **608**. The outer surface of valve **608** can be separated by a distance from the inner surface of the resealable member **622**. Advantageously, where the pressure within the lumen **610** is greater than the pressure outside the catheter assembly **100**, the internal pressure can be exerted on valve **608** to close resealable path **604**. The proximal extension of the valve **608** into the lumen **610** can also promote easier entry of a guidewire into the lumen **610** when the guidewire is introduced from the distal end of the pump. Other valves structures that may be used in place of the valve **608** are discussed in U.S. application Ser. No. 12/829,359 and in U.S. Pat. No. 7,022,100, which are incorporated by reference herein for all purposes and in its entirety.

Another embodiment of an impeller tip **602** that includes a resealable member **624** is illustrated in FIG. **16C**. The resealable member **624** can have a resealable path **630** therethrough. The resealable member **624** can optionally include a distal tapered portion. As described herein, the impeller can be coupled with the catheter body through a drive shaft **148**, which can be disposed or received within the axial lumen of the impeller or within the impeller shaft **204**. As illustrated in FIG. **16C**, a distal portion of a shaft, e.g., the drive shaft **148** or the impeller shaft **204**, can be disposed or received within the resealable member **624**. The impeller tip **602** can further include a non-resealable portion **626** having a non-resealable path **628** extending therethrough (e.g., a path that generally does not seal or close once it has been opened or created, and/or remains permanently open allowing fluid to pass therethrough). The resealable path **630** and the non-resealable path **628** can be co-linear (e.g., coaxial). As illustrated in FIG. **16C**, the non-resealable portion **626** can extend distally of the resealable member **624**. In some embodiments, the non-resealable portion **626** can partially or fully surround an outer surface of the resealable member **624**. For example, the resealable member **624** can be partially or entirely contained within the non-resealable portion **626**. As illustrated in FIG. **16C**, the non-resealable portion **626** can include the distal-most portion of the impeller tip **602**. In some embodiments, the non-resealable portion **626** can be a unitary structure that includes the hub and one or more blades of the impeller. In one embodiment, the non-resealable portion **626** can include the entire impeller body except for the resealable member **624**. For example, as discussed above, the impeller can include a hub disposed between the impeller blades and the impeller shaft **204**. The impeller hub can surround the resealable member **624**.

Advantageously, the impeller tip **602** can be configured to receive a guidewire through both the resealable path and the non-resealable path **628**. In some embodiments, the resealable path (when open) and/or the non-resealable path can have a diameter that is no more than one-half the diameter of the guidewire. Where the impeller tip **602** includes a resealable member **624** disposed therein, the resealable member can be advantageously protected from the trauma to which the outer surface of the impeller tip **602** may be exposed. In addition, the distally-extending non-resealable path can act as a guide or channel that directs the guidewire through the impeller. Furthermore, as discussed herein, the tapered shape of the distal portion of the resealable member **624** can help to reseal the resealable member **624**, as radial forces extending inwards can surround the tapered portion and help to close the resealable path. Note in this case that the non-resealable member, also made of an elastomeric material (but different

actual material), retains a level of elasticity that can stretch to a lesser degree than the resealable material to accommodate passage of the guidewire.

The impeller tip **602** illustrated in FIG. **16C** can be manufactured by first molding a soft and/or elastomeric material over at least a portion of the drive shaft **148** of the impeller shaft **204** to form the resealable member **624**. Some suitable materials for forming the member **624** include polyurethane and silicone. Some materials having low durometer, e.g., below 60 A, can be used for the resealable member **624**. In some embodiments, the material can have a durometer in the range of from about 25 A to about 55 A. For example, the material can be a polyurethane or a silicone polymer having a durometer below 60 A (e.g., in the range of from about 25 A to about 55 A). In some embodiments with a polyurethane material, the hardness can be for example, about 25 A, about 35 A, about 45 A, or about 55 A. In other embodiments, a silicone material can be used for the tip **602** and/or the resealable member **622**, **624**. The silicone material can have a hardness ranging from about 20 A to about 60 A. In some embodiments, the hardness can be about 38 A. As described above, the resealable member **624** can optionally be formed to include a distal tapered portion. The rest of the impeller, or a portion thereof, can then be molded over the resealable member **624** and the drive shaft **148**. The remainder of the impeller tip **602** can be formed from a second material (e.g., a second polymer) that is different from the material used to form the resealable member **624**. The non-resealable path **628** and the resealable path **630** can be created after the impeller is molded over the drive shaft **148** or the impeller shaft **204**. A variety of methods and/or tools can be used to create these paths, including but not limited to a drill, a needle, or a small gauge screw. In some embodiments, the paths **628**, **630** can be formed from a proximal end to a distal end of a wall of the impeller hub, e.g., distal of the distal most blade. In other embodiments, the paths **628** can be formed from a distal end of the impeller toward a proximal end of the impeller.

In use, those skilled in the art may appreciate that non-sealable (e.g., non-resealable or non-self-sealing) devices may require a constant flow of infusant in the distal direction to prevent the proximal flow of fluid or blood into the device. Advantageously, a resealable tip can allow for guidewire passage through the center of the catheter assembly **100** to ease insertion without requiring a constant flush of infusant. The tip in various embodiments the resealable tip self-seals when the guidewire is removed. Valves discussed herein provide the advantage of preventing blood from entering other portions of the catheter assembly **100**, such as the impeller shaft **204** or the lumen **234** or the bearing housing **228**. In various embodiments, valves are configured to be actuated from an at least partially open configuration to a closed configuration, such as by application of a force or pressure on one side thereof.

#### D. Sheath Having Expandable Distal End

As described herein, the pump can include a sheath assembly. The sheath assembly can control the collapse and expansion of the impeller and/or the impeller housing. In some embodiments, the distal end of the sheath assembly can optionally include one or more structures that aid in the deployment and/or retrieval of the impeller assembly.

In some embodiments, as shown in FIGS. **17A** to **17D**, the sheath assembly can include an expandable distal end **170a**, **170b**, **170c**. For example, the distal end can expand when a radial force is applied, and can contract when the radial force is removed. The distal end may also be able to expand and/or

contract repeatedly. When expanded, the distal end **170a**, **170b**, **170c** can have a conical and/or funnel-like configuration. When not expanded, the distal end **170a**, **170b**, **170c** can have a generally cylindrical (e.g., generally constant diameter) configuration, for example as illustrated in FIG. **17A**. To assist with expansion and/or contraction, the distal end **170a**, **170b**, **170c** or portions thereof may be made from materials having a different flexibility and/or elasticity (e.g., more or less flexible and/or elastic) than the material(s) used for all or a portion of the remainder of the sheath assembly. In some embodiments, the sheath assembly **162** can have at least one configuration where it is at least partially disposed over the impeller housing, catheter assembly, and/or impeller assembly. Advantageously, the conical and/or funnel-like configuration can aid the deployment and/or retraction of the impeller assembly and/or impeller housing as described herein.

As illustrated in FIG. **17A**, the distal end **170a** can include one or more axial slits **702** (e.g., 2, 3, or 4 slits). Slit **702** can extend proximally from the distal end **170a** at least partially along the length of the elongate body **174**. The distal end **170a** can also include a plurality of elongate members **704** (e.g., 2, 3, or 4 elongate members). Each elongate member **704** can be joined at one end (e.g., proximal end) to the sheath assembly. Each elongate member **704** can also have a distal end **705** that is outwardly deflectable away from axis **708**. The elongate members **704** can be separated from each other by the slits **702**. Each elongate member **704** can have a width that is defined by the distance between slits **702** and a length defined by the length of each adjacent slit **702**. In some embodiments, the elongate members **704** and slits **702** can be generally equally spaced circumferentially about the elongate body **174**. In some embodiments, the elongate members **704** can each have a length that is generally equal to or greater than the axial length of the outlet portion of the impeller housing. For example, in some embodiments, the elongate members **704** can each have a length in the range of from about 0.25 in. up to about 2.0 in. In other embodiments, the elongate members **704** can each have a length in the range of from about 0.5 in to about 0.75 in. The elongate members **704** and/or at least a portion of the sheath assembly **162** (e.g., the portion of the sheath assembly **162** that connects to elongate members **704**) can be made from a relatively elastic material (e.g., any of the elastomeric polymers described herein).

In use, an outwardly-acting radial force resulting from the radial stiffness of the impeller housing can be applied to the elongate members **704** which causes the elongate members **704** to deflect outwards, as illustrated in FIG. **17B**. For example, the axial movement of the impeller housing in the proximal direction into the sheath assembly (or distal movement of the sheath over the expanded impeller housing) can cause the elongate members **704** to deflect outwards. The outward deflection of the elongate members **704** can result in the conical or funnel-like configuration of the distal end **170a** when sheathed over an expanded section of the impeller housing. When the elongate members **704** are deflected outwards, the width of each slit **702** can increase at the distal end to define a gap **709**. In some embodiments, the elongate members **704** can be self-collapsing. For example, the elongate members **704** can be configured to return to their original configuration when the internal outward-acting radial forces are released (e.g., where the elongate members **704** are made of a relatively elastic material).

As illustrated in FIG. **17C**, the distal end **170b** of the sheath assembly can include a deformable structure **706** (e.g., a webbing) that at least partially covers one or more slits **702**. In some embodiments, the deformable (e.g., stretchable, expandable, flexible, and/or elastic) structure **706** can sur-

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round, coat, and/or cover at least a portion of the distal end **170b** (e.g., the elongate members **704**). As illustrated in FIG. **17C**, the deformable structure **706** can be an elastomeric coating (e.g., incorporating those elastomeric materials described herein). In other embodiments, the deformable structure **706** can include a spring, such as a semi-circular spring member having a straight or oscillatory pattern. In use, the deformable structure **706** can be configured to return the elongate members **704** to their original, non-conical configuration and/or prevent over-deflection of the elongate members **704** beyond their elastic limit.

In some embodiments, the elongate members **704** can be stiffer (in the circumferential and/or axial direction(s)) than the proximally-adjacent portion of the sheath assembly. Advantageously, the stiffer material can prevent or inhibit the distal-most end of the sheath assembly from folding over itself when it encounters resistance (e.g., advancing the sheath over an expanded cannula housing). In one embodiment, one or more elongate members **704** can be reinforced with a plurality of wires that extend to the distal-most tip of the elongate member **704**. In another embodiment, one or more elongate members **704** can be made from a polymer that is stiffer than the material (e.g., a second polymer) of the proximally-adjacent portion of the sheath assembly.

As illustrated in FIG. **17D**, in some embodiments the distal end **170c** of sheath assembly **162** can include an integral funnel **710** having a distal, conically-shaped portion **711**. As described further herein, the integral funnel **710** can be expandable and/or collapsible. Advantageously, the integral funnel **710** can assist in deployment and retraction of the housing while minimally increasing the profile of the pump. The integral funnel **710** can be connected to a non-expandable portion **712** of the sheath, for example, at a distal-most tip **714**. The integral funnel **710** can include an outer layer **713** and an inner layer **715** that converge at an interface **717**. The integral funnel **710** can be layered over an outer surface **716** and over an inner surface **718** of the non-expandable portion **712**. Accordingly, as illustrated in FIG. **17D**, at least a portion of the inner layer **715** can reside, at least temporarily, within the lumen of the sheath assembly **162**. The integral funnel **710** can be connected to either the outer surface **716** or the inner surface **718** of the sheath. In some embodiments, the funnel **710** can be a distal extension of distal end **170** that is folded over the non-expandable portion **712**.

The integral funnel **710** can be slideable over the outer surface **716** and/or the inner surface **718** of the non-expandable portion **712**. The contact surfaces between the non-expandable portion **712** and the integral funnel **710** and/or between the outer layer **713** and the inner layer **715** can be lubricated, e.g., using a silicone lubricant, to establish and/or maintain slideability and/or low friction. The integral funnel **710** can be made from a thin, flexible material, such as a polyurethane polymer. In some embodiments, the integral funnel **710** can be made from a material that is more flexible and/or elastic than the material that is used for all or a portion of the remainder of the sheath assembly. In some embodiments, the material used for the integral funnel **710** can have one or more membrane-like qualities. In use, the axial movement of the housing **202** (not shown) can frictionally engage the integral funnel **710**, causing the integral funnel **710** to deploy or retract. For example, in embodiments where the outer layer **713** is affixed to the non-expandable portion **712** of the sheath, axial movement of the housing **202** in a distal direction can cause the inner layer **715** to translate distally (e.g., slide distally along the inner surface **718** of the sheath), thus deploying the conical portion **711** (e.g., pulling the conical portion **711** out of the sheath). Axial movement of the

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housing in a proximal direction can cause the inner layer **715** to translate proximally (e.g., slide proximally along the inner surface **718** of the sheath), thus retracting the conical portion **711** into the sheath (e.g., pulling the conical portion **711** into the sheath). The thin, flexible material of the conical portion **711** can advantageously allow the conical portion **711** to deform upon retraction into the sheath.

In embodiments where the inner layer **715** is affixed to the non-expandable portion of the sheath, axial movement of the housing **202** can cause the outer layer **713** to translate. For example, distal movement of the housing can cause the outer layer **713** to slide distally along the outer surface **716** of the sheath. Proximal movement of the housing can cause the outer layer **713** to slide proximally along the outer surface **716** of the sheath.

In some embodiments where the funnel **710** is a distal extension of the non-expandable portion **712** that is folded over the non-expandable portion **712**, the funnel **710** can slide distally as the non-expandable portion **712** is moved proximally. In use, as the non-expandable portion **712** is moved proximally, the funnel **710** can slide distally to unfold and surround the impeller assembly **116**.

#### IV. Methods

Various methods and techniques are discussed above in connection with specific structures of heart pumps. The following elaborates on some aspects of these techniques and methods. The following discussion is to be read in light of and freely combined with the foregoing discussion.

##### A. Retracting and Deploying the Impeller Housing By Way of the Impeller Deployment Assembly at the Proximal End of the Catheter Body

As discussed above, in various embodiments the heart pump **10** is inserted in a less invasive manner, e.g., using techniques that can be employed in a catheter lab. Various general techniques pertinent to the heart pump **10** are described in U.S. patent application Ser. No. 12/829,359, filed on Jul. 1, 2010, and entitled Blood Pump With Expandable Cannula, which is incorporated by reference herein in its entirety and for all purposes.

Because the catheter assembly **100** is to be delivered through a small access site, it can be important to ensure that the impeller housing is reliably deployed and retracted, as described above. A clinician may begin a heart pumping procedure by introducing the catheter assembly **100** into the patient percutaneously, e.g., by urging the catheter assembly through the femoral artery and into a heart chamber. Because the impeller and impeller housing are advanced through a narrow artery in some embodiments, the impeller and impeller housing can initially be inserted into the patient in a retracted, or collapsed (or low profile), state, as described above. Once the distal end of the catheter assembly **100** (including the impeller housing) has reached the desired operating location (e.g., a heart chamber), the clinician can deploy the impeller housing into an advanced or expanded configuration.

One method of deploying the impeller and/or diffuser is by using the impeller deployment assembly **800**, which can be located near the proximal end of the catheter assembly. As shown in FIGS. **15A** and **15B**, the clinician can rotate the nut **804** (clockwise or counter-clockwise depending on the threading) such that the nut **804** translates from a distal position to a proximal position. In turn, the flow diverter **806**, the catheter body, and the impeller housing can also translate

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from a distal position to a proximal position and thereby advance the impeller distally into a wider portion of the impeller housing to allow for deployment of the impeller hub 208 and blades 212. Thus, in some embodiments, the clinician can deploy the impeller, located at a distal end of the catheter assembly, by rotating a nut disposed near the proximal end of the catheter assembly.

In some embodiments, the impeller 200 and housing 202 can be axially displaced relative to their operational positions during delivery of the distal end to the heart (e.g., the impeller and housing can be delivered to the vasculature in an axially separated configuration). As used in this context, “axially displaced” includes configurations where there is axial movement of the impeller 200 relative to any portion of the housing 202 prior to or during the process of delivery. For example, axial displacement includes conditions in which the impeller 200 is moved from a first position near a proximal end port (outlet for left side support or inlet for right side support) of the housing 202 to a second position distal the first position. The second position can be one that is still between the proximal end port and a distal end port (inlet for left side support or outlet for right side support) of the housing 202. The first position may be the operational position of the impeller 200 relative to the housing 202. Axial displacement also includes conditions in which the impeller is located proximal of an operational position, e.g., at a location proximal of a proximal end port of the housing 202, including being disposed within a non-expandable portion of the heart pump. When the clinician delivers the distal end of the heart pump to the heart chamber, rather than delivering the distal end with the impeller housing disposed over the impeller blades, the impeller housing can be in a proximally displaced position or retracted configuration (or distally displaced position or advanced configuration in other embodiments) with respect to the impeller, such that it is axially moved from the operational position, as discussed above.

In some embodiments, the impeller and the housing can be delivered in series (with the impeller being delivered before the housing, or vice versa). For example, in one embodiment, the impeller housing 202 is first advanced into position, e.g., in the heart. The housing 202 may then be expanded if the housing has expanded and compressed configurations. Thereafter the impeller 200 may be positioned, e.g., advanced through a catheter body similar to the catheter body 120 to be positioned within the impeller housing 202. Thereafter the impeller 200 can be rotated by a source of rotational energy. In various embodiments, the source of rotational energy can comprise a motor positioned outside of the patient to drive a shaft similar to the shaft 148. In other embodiment, the source of rotational energy can comprise a motor that is miniaturized to be positionable within the patient, as discussed in U.S. Pat. No. 7,070,555, which is incorporated by reference herein for all purposes and in its entirety. In another embodiment, the distal end of the impeller 200 can be configured to be advanced into position in the patient and, at a later stage of a procedure, the impeller housing 202 can be positioned thereover. In one technique, the impeller 200 is positioned in the heart chamber (or wherever the procedure is to occur), the clinician can then advance the impeller housing over the impeller blades and begin operating the heart pump. For removal of the catheter assembly from the patient after the procedure, the clinician can retract or displace the impeller housing proximally to axially displace and/or separate the impeller from the impeller housing.

The configurations enabling displaced or serial delivery also can decouple the design of the impeller housing 202 from the complexities of the design of the impeller 200. For

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example, the impeller housing 202 can have a greater range of expansion from a collapsed state to an expanded state. If no structures are disposed inside the housing 202 in the collapsed state, greater compression and a lower crossing profile can be achieved compared to where the housing 202 must be sized in the collapsed state to accommodate the impeller 200 in its collapsed state. This provides one or more of the benefits of access through smaller vessels, in smaller patients, or a larger expanded size in standard patients through typical access (e.g., femoral vessel). Similarly, greater compression of the impeller 200 may be possible if the impeller 200 is delivered using a dedicated compression sheath or device that is not required to expand and/or to be present around the impeller during operation. As a result, larger blades may be delivered from the same collapsed profile, providing the advantages of higher flow discussed above. More details of serial delivery of blood pumps are discussed in U.S. Pat. No. 7,022,100, which is incorporated by reference herein for all purposes and in its entirety.

Once the impeller is deployed, the clinician can conduct the procedure, e.g., by running the heart pump within a heart chamber. Once the procedure is finished, the clinician can remove the catheter assembly from the patient by retracting the impeller. The clinician can simply rotate the nut 804 in a direction opposite to that rotated for deploying the impeller. The nut can then translate from the proximal position to the distal position, which in turn can cause the flow diverter 806, the catheter body, and the impeller housing to also translate from the proximal position to the distal position. The impeller can thereby be retracted proximally into an area near the outlet 802 to reduce the profile of the pump upon collapsing into the sheath. Thus, the clinician can both deploy and retract the impeller by rotating a nut located near the proximal end of the catheter assembly.

#### B. Controlling the Collapse and Deployment of the Impeller Housing with the Sheath Assembly

As mentioned above in Section IV(A), it can be advantageous in certain embodiments to enable a clinician to deploy and retract the impeller assembly prior to and after a heart procedure. One method of collapsing the impeller housing can be performed by advancing the sheath assembly 162 distally over the impeller housing to collapse the impeller assembly, e.g., for removal of the catheter assembly from the patient after a heart procedure. As mentioned above, elongate body 174 of the catheter assembly 162 can be slidably disposed over the catheter body 120. The clinician can distally advance the elongate body 174 over the impeller housing, or alternatively proximally retract the catheter body 120 such that the impeller housing collapses into the elongate body 174 of the sheath assembly 162.

As FIGS. 17A-D illustrate, the sheath assembly can have expandable distal ends 170a, 170b, 170c, that expand when a radial force is applied. Thus, when the clinician advances the elongate body 174 of the sheath over the impeller housing, the impeller housing can contact the distal end 170 and can induce a radial force that causes the distal ends 170a, 170b, 170c, to expand in order to aid in retraction of the impeller assembly. Similarly, when the clinician slides the elongate body 174 in a proximal direction, the impeller assembly can deploy through the distal end 170 of the catheter assembly 162, because the distal ends 170a, 170b, 170c, can contract when a radial force is removed (or not applied). Thus, the clinician can reliably deploy and retract the impeller assembly by sliding the elongate body 174 of the sheath relative to the catheter body 120. In other embodiments, the sheath



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assembly need not have expandable distal ends as described above. The clinician can therefore simply deploy the impeller assembly 116 by providing relative motion between the elongate body 174 of the sheath and the impeller assembly, e.g., by retracting the elongate body 174 from the impeller assembly, and can collapse the impeller assembly by providing relative motion between the elongate body 174 of the sheath and the impeller assembly 116, e.g., by advancing the elongate body over the impeller assembly. The distal end of the elongate body 174 can therefore effectuate collapse of the impeller assembly 116 without using the expandable distal ends described above. In embodiments where the impeller assembly is self-expanding, the retraction of the elongate body 174 from the impeller assembly 116 or extension of the impeller assembly 116 out of the elongate body 174 can release the impeller assembly to self-expand.

It will be apparent to those skilled in the art that various modifications and variations can be made in the present embodiments without departing from the scope or spirit of the advantages of the present application. Thus, it is intended that the present application cover the modifications and variations of these embodiments and their equivalents.

What is claimed is:

1. A heart pump comprising:

a catheter body comprising a proximal end, a distal end, and an elongate body extending therebetween;  
an impeller coupled with the distal end of the catheter body and comprising an axial lumen passing through a distal end of the impeller, the impeller comprising a blade; and  
a tip positioned distal of the blade of the impeller, the tip comprising a resealable member having a resealable path therethrough,

wherein the tip further comprises a non-resealable portion having a non-resealable path therethrough, the non-resealable path has a proximal end disposed distal of the blade of the impeller and of the resealable path, the proximal end of the non-resealable path having a circumference disposed around the axis of rotation of the impeller that is smaller than a circumference of the resealable member disposed around the axis of rotation of the impeller, wherein a distal surface of the non-resealable portion tapers distally and inwardly towards the axial lumen, wherein a distal-most end of the distal surface defines an access port to receive a guidewire, and wherein the non-resealable path is adapted to direct the guidewire through the impeller.

2. The heart pump of claim 1, wherein the resealable member comprises a distal tapered portion.

3. The heart pump of claim 1, wherein the resealable member comprises a first elastomeric material and the tip comprises a second material that is different from the first elastomeric material.

4. The heart pump of claim 1, wherein the impeller is coupled with the catheter body through a drive shaft.

5. The heart pump of claim 4, wherein the resealable member is coupled to the drive shaft of the impeller.

6. The heart pump of claim 5, wherein a distal portion of the drive shaft is disposed within the resealable member.

7. The heart pump of claim 5, wherein the drive shaft is disposed within the axial lumen of the impeller.

8. The heart pump of claim 1, further comprising an impeller shaft coupled to the impeller, wherein the non-resealable portion and the resealable member are positioned distal of the impeller shaft.

9. The heart pump of claim 1, wherein the non-resealable portion surrounds an outer surface of the resealable member.

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10. The heart pump of claim 1, wherein the non-resealable portion comprises a distal-most portion of the impeller tip.

11. The heart pump of claim 1, wherein the non-resealable portion is a unitary structure comprising a hub and one or more blades of the impeller.

12. The heart pump of claim 1, wherein the impeller tip is configured to receive a guidewire through the resealable path and the non-resealable path.

13. The heart pump of claim 12, wherein, when the guidewire is removed from the axial lumen, the resealable path closes and the non-resealable path remains open.

14. The heart pump of claim 12, wherein a diameter of the resealable path when open is no more than one-half a diameter of the guidewire.

15. The heart pump of claim 1, wherein the impeller tip comprises a valve that extends proximally into the axial lumen of the impeller.

16. The heart pump of claim 15, wherein the valve is a duck bill valve that tapers proximally into the axial lumen of the impeller.

17. The heart pump of claim 1, wherein the impeller comprises an impeller body, the impeller body and the resealable member having a monolithic configuration.

18. The heart pump of claim 1, wherein the impeller is an expandable impeller having an expanded configuration and a collapsed configuration.

19. The heart pump of claim 1, further comprising an expandable impeller housing, the impeller disposed in the expandable impeller housing.

20. The heart pump of claim 19, further comprising a sheath disposed over at least a portion of the distal end of the catheter body, the sheath configured to control the collapse and expansion of the impeller housing.

21. The heart pump of claim 1, wherein the resealable and non-resealable paths are co-axial.

22. The heart pump of claim 1, wherein the distal surface comprises a first end and a second end, the second end disposed proximal the first end, the first end being a first distance from a central longitudinal axis of the axial lumen, the second end being a second distance from the central longitudinal axis, the first distance being less than the second distance.

23. A heart pump comprising:

a catheter body comprising a proximal end, a distal end, and an elongate body extending therebetween;

an impeller coupled with the distal end of the catheter body and comprising a lumen passing through a distal end of the impeller, the impeller comprising a blade; and  
a tip positioned distal of the blade of the impeller, the tip comprising:

a seal; and

an enclosure having a distal surface and enclosing a volume within which the seal is disposed, the enclosure having a circumferential wall surrounding an access port defined by a distal-most end of the distal surface, the distal surface of the enclosure tapering distally and inwardly towards the lumen, the tip comprising a resealable member having a resealable path therethrough and a non-resealable portion having a non-resealable path therethrough, the non-resealable path having a proximal end disposed distal of the blade of the impeller and of the resealable path, the proximal end of the non-resealable path having a circumference disposed around the axis of rotation of the impeller that is smaller than a circumference of the resealable member disposed around the axis of rotation of the impeller,

wherein the seal is accessible through the access port and, when open, is configured to connect the access port with



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the lumen, and wherein the access port is adapted to direct the guidewire to the lumen of the impeller through the seal.

**24.** The heart pump of claim **23**, wherein, when the guidewire is removed from the lumen, the seal closes. 5

**25.** The heart pump of claim **24**, wherein, when the guidewire is removed from the lumen, the access port remains open.

**26.** The heart pump of claim **23**, wherein the distal surface comprises a first end and a second end, the second end disposed proximal the first end, the first end being a first distance from a central longitudinal axis of the lumen, the second end being a second distance from the central longitudinal axis, the first distance being less than the second distance. 10

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